Faculty of Science and Engineering
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Dynamic Fatigue Assessment of Fixed Offshore Platforms

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Declaration

This thesis contains no material which has been accepted for the award of any other degree or diploma in any university.

To the best of my knowledge and belief this thesis contains no material previously published by any other person except where due acknowledgement has been made.

The following publications have resulted from the work carried out for this degree.

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Abstract

In this thesis a practical method for dynamic fatigue assessment of jacket-type offshore structures is investigated using existing experience and the procedures available within the industry. Fatigue is a primary mode of failure for steel structures that are subjected to dynamic loads. For offshore structures the most significant dynamic loads are those induced by wave action. Since wave loads on offshore platforms varied with time they produce dynamic effects on structures.

Estimating the fatigue damage for offshore structures is a complicated problem, requiring accurate dynamic analysis of the structure. The spectral approach to fatigue analysis is an attempt to account for the random nature of a confused sea in a rational manner. The nonlinear structural behaviour incorporated using methods based on equivalent linearization and frequency domain expansions. Frequency domain-spectral techniques are used to generate statistical measures of random structural response via the combination of structural transfer functions with an appropriate wave spectrum, to produce response spectra. Statistical measures of random response are quantified by the evaluation of spectral moments. Care must be taken to ensure that the full response of the structure is determined.

The method is most appropriate when there is a linear relationship between wave height and the wave-induced loads, and the structural response to these loads is linear. Frequency domain-spectral analysis must linearly approximate P-δ and foundation effects and are not able to directly capture the nonlinear wave loading due to the requirement for problem linearization. However, the numerical efficiency and ability to provide a realistic representation of the response process, makes this technique a very practical assessment tool for accurate fatigue assessments of fixed Jacket type offshore platforms.

An accurate procedure for the random vibration computation of structure is developed using frequency domain techniques. Adaptations to the basic method have been developed to account for various non-linearity. To illustrate the aforementioned methodology, a jacket type offshore platform in the Persian Gulf has been selected and the practical use of the method in the design of fixed jacket type offshore platforms is recommended.

Acknowledgements

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I dedicate this dissertation to my loved ones for their inspiration throughout my academic endeavours and making all this possible.

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Chapter 1 Introduction

Fixed offshore platforms including steel jacket, concrete caisson, floating steel and even floating concrete are economically feasible for installation in water depths up to about 520 m. The Persian Gulf region is one of the important energy zones in the world with numerous oil and gas fields and offshore structures to extract the valuable energy resources. These offshore structures are mainly fixed jacket type platforms, which are cost effective since the maximum installation depths of jackets are 70 m (Asgarian, 2009). The primary structural components of jacket type offshore structures include topside, jacket and pile foundations. The most common used offshore structure is a jacket structure, which comprises a prefabricated steel support structure (jacket) extended from the sea bed, connected with piles at the sea bed to some height above the water surface level and a steel deck (topside) on the top of the jacket. A general view of the structural model including the jacket and topside is shown in Figure 1-1.

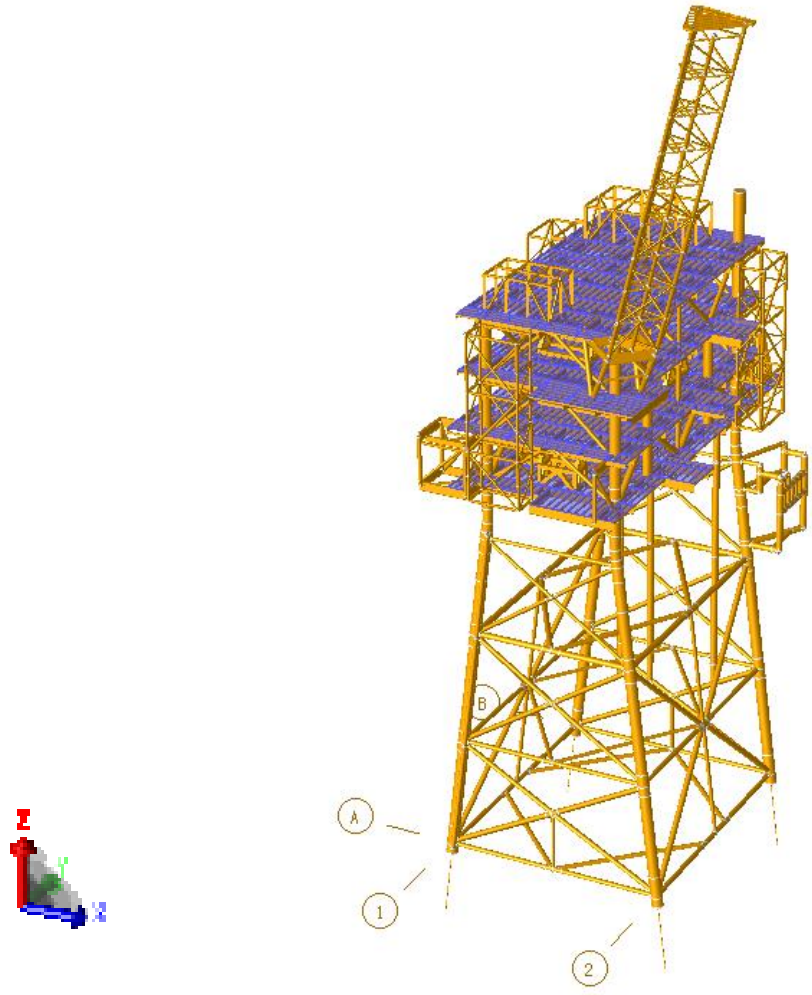

Figure 1-1 General view of SACS structural model

The Platform description and environmental data is tabulated in Table 1-1.

Table 1-1 Platform General Data

Jacket dimension at mudline (EL -41.3 m)	30.15 (m)×36 (m)
Jacket dimension at work point (EL 7.3 m)	18 (m)×36 (m)
Upper Deck dimension at EL 35.5 m	41.2 (m)×23.2 (m)
Lower Deck dimension at EL 13.3 m	51.6 (m)×23.2 (m)
Topside Operating Weight	1140 (MT)
Water Depth	42.72 m

Fatigue is a primary mode of failure causing degradation in the long-term integrity of offshore structures. Fatigue damage accumulation experienced by an offshore structure is mainly caused by dynamic effects of small and medium sized ocean waves that are inertia dominated. Dynamic effects are clearly important in the determination of a platform's ultimate strength and cyclic degradation behaviour. For dynamically sensitive structures, the effects of dynamics and structural response become more important. In this regard, the structure must be adequately modelled to obtain realistic results for fatigue performance.

The elements contributing to dynamic effects are mostly excitation frequency, natural frequency, effective mass and stiffness of structure and the overall damping. Modal analysis is carried out to identify the eigen-frequencies and mode shapes as essential factors contributing to structural dynamic response magnifications due to excitation loads.

A structure's dynamic behaviour is significantly affected by the soil characteristics and the pile–soil interaction. The actual structure will be less stiff than estimated from a linear analysis because of displacement dependent effects. This will tend to increase the deflection of the structure, thereby reducing its effective stiffness (ABS, 2004). Finite deflection of the pile (the P-δ effect) is accounted for by using the equivalent pile stub based on pile–soil-structure interaction, which depends on pile head forces, pile stiffness, etc. The pile is represented by a beam column on a nonlinear elastic foundation and the finite difference solution method is used to solve the pile model. The structure resting on the piles is represented as a linear elastic model.

The random nature of the wave loading can be captured in the frequency domain spectral method using a wave spectrum and a structural transfer function, which is based on the linear concept. A sufficient number of suitably spaced frequencies are selected so that the transfer functions are adequately defined over the relevant frequency range where response is expected. In this manner, the peak wave spectrum period is properly mapped and the response effects of interest, including responses around structural resonances, wave load cancellation or enhancement points, are depicted.

The method is most applicable when there is a definable relation between wave height and stress ranges at the connections. This could be best implemented for a stationary process where the excitation is the elevation of the sea's surface at a point and the response of interest is the hot spot stress ranges. These assumptions are most applicable for low to moderate sea-states. Since these are the sea-states of interest in fatigue studies, these assumptions can reasonably be accepted. The basic method is improved to capture various non linearities. An enhanced frequency domain spectral technique is further developed as the relevant response process and the suitability of the method is investigated as a practical assessment tool.

1.1 Objectives

This PhD thesis has advanced the practice of fatigue assessment of offshore structures in frequency domain by accounting for non-linear system responses with due consideration of the system vibration characteristics and employing a rigorous calibration process. The applicability of the proposed approach is demonstrated in detail by applying the aforementioned methodology to a fixed jacket type offshore platform in the Persian Gulf.

The PhD researcher has had the opportunity to work in numerous FEED (Front End Engineering Design) and detail design projects comprising of fixed jacket type offshore platforms. Initially, a literature review of the industry experience and existing knowledge is conducted to identify recent important advances in dynamic fatigue assessment of fixed offshore platforms. Furthermore, the most appropriate design methods that meet functionality, safety and economical aspects of structural design for fatigue damage are investigated.

In this thesis dynamic fatigue damage of fixed offshore platforms in low to moderate sea-states is investigated with appropriate dynamic tools. Moreover, it is demonstrated how to develop an effective procedure to maintain fatigue life of fixed jacket type offshore platforms that are

subjected to hostile marine environments. In dynamic fatigue assessment a wave scatter diagram is used to represent the long-term statistics of the sea-state.

Actual wave steepness is determined using a suitable calibration process based on matching of global response parameters. The calibration determines a wave steepness value that matches the spectrally calculated response to a deterministically calculated response. The effect of wave frequency on wave loading and structural response is accounted for by using transfer functions for evaluating the response in each random sea-state. The emphasis is made on a procedure, which can be fit through existing design codes of practice. Finally, some recommendations will be made for future development work.

1.2 Background

Offshore platforms are one of the most important structures in exploration and production of oil and natural gas. Since its inception sixty years ago, the offshore structures industry has been growing at a fast rate. The literature on fixed offshore structures is huge. The failure of structure may occur due to the fatigue of the structure in the low to moderate sea-states as well as extreme response to the severest sea (Kim, 2008). Due to large investment that offshore platforms represent and the catastrophic consequences of their failure, safe, efficient and economical platform design approach is of prime importance.

Fatigue has become an important consideration both at the design stage and during maintenance for structural integrity assessment procedures. For reliable design of offshore platforms care should be taken on dynamic behaviour of jacket type offshore platforms to environmental loads. Dynamic analysis of offshore platforms can be performed for extreme loads (Azarhoushang, 2010a) or for long term effects (fatigue degradation), which is the subject of this research study. Dynamic effects are clearly important in the determination of platform ultimate pushover strength incorporating inertia and resonance effects, strain rate effects on yield stress and soil properties, and cyclic degradation behaviour (Frieze, 1997).

In addition to using a dynamic analysis, it is essential to use a stochastically defined sea-state in place of a single design wave. Such an analysis is essential in designing against the first excursion failure and an adequate fatigue life. The stochastic approach based on frequency domain spectral analysis or random time domain simulations enables the random nature of environment to be reflected. This approach leads to a more realistic solution and usually results in reduced design loads, which allow lighter and more efficient structures (Iraninejad, 1988).

The methodology used here is a frequency domain analysis using spectral density functions and the transfer function approach to model the response spectrum. This approach is useful to handle nonlinear effects when the wave statistics of random sea are not changing (due to existence of short periods in fatigue loading environment) and water surface elevation can be properly described by wave power spectra.

The most commonly used offshore platform is the jacket-type structure, which comprises of three main parts, namely the jacket itself, the deck and the piled foundation. The jacket consists of steel frames that extend to the mud line and are then supported by piles. Most steel offshore support structures are three-dimensional frames fabricated from tubular steel members. Fatigue life is one of the major concerns for offshore platforms since the utilization of tubular members gives rise to significantly high stress concentrations in the joints. In some cases, fatigue cracking has led to member severance, resulting in a consequent reduction of overall structural integrity.

The characteristics of fatigue loading on offshore structures such as fixed jacket type offshore platforms are dependent on environmental conditions and structural features. Environmental load assumptions introduce major sources of uncertainty in the design process. Despite of the engineering complexities and uncertainties, the optimum design of a structure with random response constraints is investigated in the this thesis.

1.3 Significance

Fatigue is a significant hazard causing degradation in the long-term integrity of offshore structures. The weld toes at tubular intersections are particularly vulnerable to fatigue failure in offshore structures due to the high local stress concentrations. The fatigue behaviour of welded tubular joints has been the focus of several major international research programs. Due to the large investment that offshore platforms require and the catastrophic consequences of their failure, reliable fatigue assessment procedures are required at the design stage. Owing to the variations in the controlling parameters, the results of the analyses are subject to uncertainties.

A comparative research is carried out to ensure the safe and reliable operation of such structures. This comparison is useful in developing methods to predefined levels of accuracy. Failing to properly incorporate dynamic effects will result in an incorrect evaluation of fatigue life. It can be clearly seen that calculated fatigue life is significantly higher than reality when

calibration is not undertaken (refer to Appendix B). This suggests the need to reconsider the models that have been deemed to be trustworthy so far.

The dynamic components of fatigue loading are unlikely to govern the bulk of the steel in the structure, provided the effects of flexibility are considered from an early stage in concept development. A relatively low weight growth can be achieved from a strong awareness of dynamic response effects and careful attention to the interaction between platform dynamic characteristics, wave loading and dynamic response. These experiences demonstrate the importance of a reliable assessment of dynamic response and the need to incorporate these effects at a very early stage in design development.

Methods to reflect the nonlinear stochastic dynamic behaviour in the frequency domain are assumed to provide the most accurate result and preserved as a point of reference to estimate the accuracy of simplified methods, which are all based on some kind of linearization theory. The research outcomes will hopefully supplement previous knowledge on fatigue assessment for dynamically responding structures subjected to random non-linear wave loading. Considering the significance of fatigue failure, extensive attention is granted to the development of guidance on safe prediction of fatigue performance with good awareness of the parameters influencing the dynamic response of the structure.

1.4 Methods of analysis

Fatigue is the process of damage accumulation initiated by material yielding due to sliding of atomic layers under cyclic stresses that develop into plastic deformation causing long term degradation to the integrity of offshore platforms.

The integrity of these structures is maintained in two stages. The first is the design stage, which is the main focus of the research program and discussed further in detail. The second stage is monitoring with underwater non-destructive inspections such as ultrasound, X-ray or eddy current. These measurement techniques could provide a robust and sensitive means for early detection and tracking of fatigue damage at an early stage. This will facilitate the maintenance scheduling to improve safety and reduce operating costs (Hillis, 2011). If any crack is discovered in service, crack growth analysis using techniques such as fracture mechanics will be carried out to assess the severity of the condition and to plan possible remedial actions.

Methods of analysis are probably the more reliable part of the design process. Methods are required that take into account the effect of randomness in structural properties and relate the

frequency content of the random seas to the fundamental natural mode of the structure (Ko, 1988).

Three notable methods of fatigue assessment at design stage are the simplified method, the spectral method and the deterministic method. The simplified method can be classified as an indirect fatigue assessment method and is often used for fatigue screening tools to identify fatigue sensitive areas of the structure. If the structural detail does not meet the requirement of simplified methods, it can be assessed with more rigorous techniques (ABS, 2010).

Spectral-based fatigue assessment is referred to as a direct method because it generates results in terms of fatigue life. This method is based on the stress range transfer function, which relates the hot spot stress and wave frequency for unit wave height. The hot spot stress (or strain) method has become the most commonly used approach for fatigue design of circular hollow section (CHS) connections. The accuracy of calculated long-term stress distributions depends mainly on the accuracy of the stress transfer functions that are cornerstones of a probabilistic analysis (Vugts, 1978). Spectral analysis is the most comprehensive analysis procedure, which takes account of the random nature of wave environment and is suitable for dynamically responding structures. This procedure should be used for the final verification of all structures unless they are located in areas that are known to have benign fatigue climates where dynamic effects can be ignored.

Deterministic method of fatigue assessment is a simplified version of the spectral method (ABS, 2010). It uses a series of periodic waves with different heights and periods to evaluate structural response, but does not reflect the true frequency content of the wave conditions. Deterministic method is highly sensitive to discrete deterministic wave selection to properly represent the fatigue environment. This procedure may be used for screening during initial design phases or for final verification of the design of structures in shallow and medium water depths where dynamic effects can be neglected.

Simplified method uses the most simplified representation of the long term wave climate and the associated loading. A single periodic wave is used to estimate the long term stress statistics from the long term wave height statistics. This method requires the least computational effort of the three. It is appropriate for screening during initial design phases or for final verification of the design of structures in very benign fatigue environments.

1.5 Research Method

For the purpose of fatigue assessment, an analytical representation of the structure (refer to Figure 1-1) is considered with the loadings and restraints using SACS software (refer to SACS input files in Appendix A). The primary structural components of jacket type offshore structures include deck, jacket and piled foundations. The piles and surrounding soil layers are replaced with equivalent elements called pile stub that have identical pile–soil lateral characteristics.

Considering natural variability in real sea waves, a probabilistic approach to define the wave environment and its resulting stresses is preferable to deterministic methods (refer to Section 1.4), which is followed in this research study. The effect of loading direction is considered with 45 degree intervals. Since the natural period of the structure (refer to Table 1-3) is in the range where there is sufficient wave energy (refer to Table 1-2) to excite significant dynamic response, the dynamic structural response needs to be considered in the fatigue analysis (Johansen, 2003).

In order to generate the peaks and valleys of the transfer function accurately, natural frequencies should be included with addition of at least three closely spaced frequencies on each side of the primary and secondary modes of the structure. For the wave response analysis, the initial frequency grid is modified in the vicinity of the first natural period. The revised frequency grid adequately describes the frequencies of the platform, cancellation and enhancement effects as well as the peak and valley period of the transfer function curve (refer to Figure 1-2).

Table 1-2 Directional wave scatter diagram – 0 degrees

4.25								1		
3.75								1		
3.25							1	1		
2.75							5	1		
2.25						6	34			
1.75					1	165	39	1		
1.25				1	246	394	1			
0.75				705	1141	54				
0.25		1	100	1262	167					
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 1-3 Frequencies and generalized mass

MODE	FREQ. (CPS)	GEN. MASS	EIGENVALUE	PERIOD (SECS)
1	0.297	5.78E+03	2.88E-01	3.37
2	0.526	4.99E+03	9.17E-02	1.90
3	0.728	3.81E+03	4.78E-02	1.37
4	1.479	1.26E+02	1.16E-02	0.68
5	1.547	4.55E+02	1.06E-02	0.65
6	1.645	2.61E+03	9.36E-03	0.61
7	2.037	2.58E+03	6.10E-03	0.49
8	2.434	8.12E+03	4.28E-03	0.41
9	2.658	3.43E+03	3.59E-03	0.38
10	2.690	5.61E+03	3.50E-03	0.37

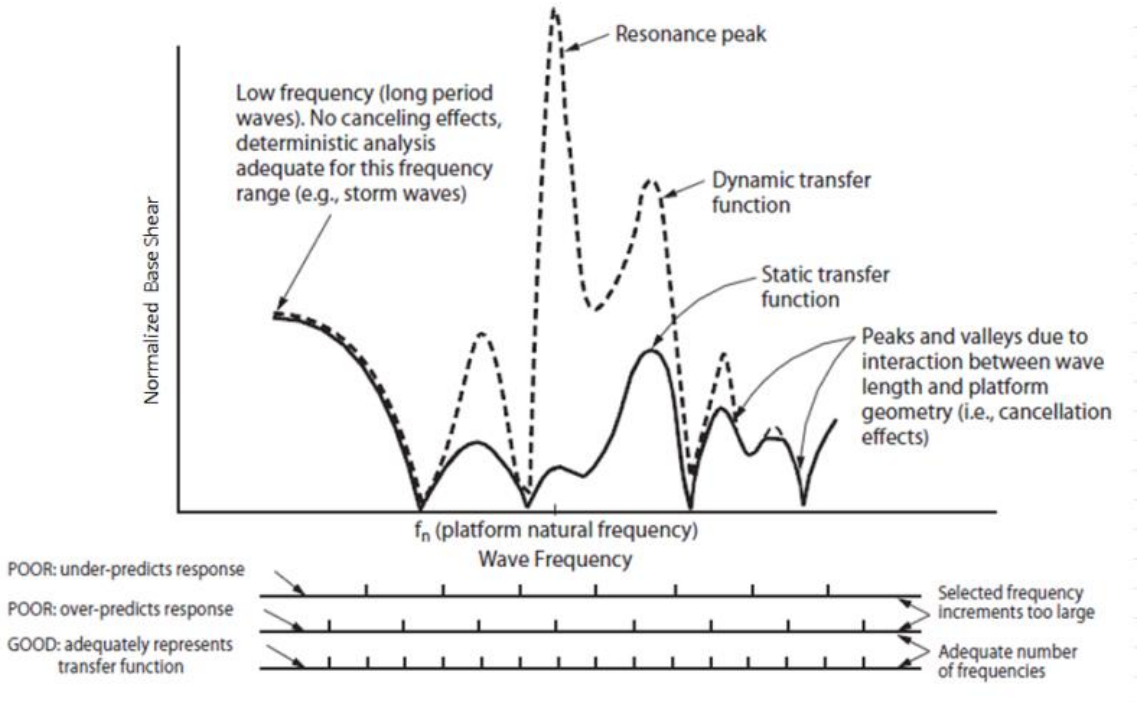

Figure 1-2 Selection of Frequencies for Detailed Analyses

The selected frequency grid includes the relevant frequency range where response is expected. The peak wave spectrum period is carefully mapped. If the dynamic amplification of the structural response is significant, special attention must be paid to the high frequency cut-off point (Vugts, 1978). Proximity of a structure resonant frequency with a wave load cancelation frequency can lead to the suppression of dynamic response effects. For this reason, a high frequency cut-off should be considered, so wave cancellation effects do not occur at higher frequencies.

The aim of the fatigue assessment method is to establish a good balance between complexity and accuracy in the prediction of the fatigue strength. Spectral analysis techniques account for the random nature of the wave environment. Since the method is based on some kind of linearization principle, it does not directly reflect response nonlinearity. However, for the determination of transfer functions in engineering applications, the linearity demand can be somewhat relaxed by an appropriate selection of the wave height input (ISO19902, 2007).

Alternatively, the stress transfer functions may be determined by performing global stress analyses in the time domain by stepping a full wave cycle past the structure. For drag dominated structures where nonlinear effects are more severe, time domain techniques are superior to other techniques. A realistic representation of the response process could be obtained by random time domain methods. Since time domain simulations are very time consuming, it is desirable to develop simple methods for fatigue analysis, especially during the initial design stages.

The frequency domain-spectral technique is superior to other techniques in parametric studies. The main advantages are numerical efficiency and realistic representation of the response process. It is also regarded as a very practical tool for site specific assessments of offshore platforms with a clear perception of the factors affecting the response at initial phase of the analysis.

However, these methods still require some theoretical development to reflect the free surface effects (Leira, 1990). In this regard an empirical modification near the free surface (Wheeler stretching) or an improved linearization method that includes inundation effects can improve fatigue assessment.

The heights of the regular waves used in the determination of the transfer functions shall be selected in a suitable manner to allow an appropriate level of non-linear (drag) action due to waves in the linearized calculations. This is achieved by calibrating the wave steepness, which matches the spectrally calculated range of applied wave action to the quasi-static calculated

range of applied wave action for the structure. For this purpose, the sea-state at the centre of the fatigue damage scatter diagram that makes the most contribution to the fatigue damage is used.

Constant wave steepness is considered to develop the transfer function. The constant-transfer function method will not only be sufficiently accurate but will also save time. However, this allots unrealistically large wave heights at low wave frequencies. Therefore, the wave heights at large wave lengths (low wave frequencies) are limited to a wave height corresponding to the one year return period as a maximum. A minimum wave height is also limited to 0.3 m (API, 2007).

To incorporate the structure's dynamic characteristics, fatigue assessment is carried out with dynamic approach in the research method. This will require the use of "Wave Response" module of SACS to generate the wave loading. The procedure to run a static fatigue analysis for cyclic wave forces is the same except that "Sea-state" module of SACS program is required to generate the wave loading.

Since the dynamic module in SACS uses the linear theory (i.e. modal superposition), linear foundation super elements are automatically created at each pile-head by the "*PSI*" module of SACS. Pile stubs of appropriate stiffness are modelled as equivalent linear foundation for evaluation of fatigue damage.

The dynamic analysis of a platform subjected to the design wave is normally performed for steady state conditions since it would be illogical to assume that the sea was at rest before waves arrived with their maximum amplitudes (Ko, 1988). A steady state structural response can be developed when the transient effects are negligible due to damping. For linear systems the response for a steady state harmonic excitation can be easily obtained in a closed form.

For spectral analyses, the loading specified to develop a transfer function is not the actual loading (fatigue environment) that causes fatigue damage, but it is rather the one that is determined by using the calibrated wave steepness value. The resulting wave heights should further be compared to the elevations of plan framing levels near the water surface, to ensure that no discontinuities in the applied wave action are likely to occur. Where appropriate, some final adjustment should be made (ISO19902, 2007).

The structural response under random loading is certainly a random process. Statistical definition of the random response could be obtained from spectral moments. Since the fatigue damage is a non-ageing effect process that means the load sequence interaction is negligible,

the spectral parameters of a stress power spectrum can be used to obtain the equivalent stress range. Fatigue damage is calculated by Miner's rule based on the assumption that it is only dependent on the current stress states. Therefore, the total damage due to a single sea-state is the linear summation of the fractional damages caused by individual stress ranges (Kam, 1990).

1.6 Solution techniques

Fixed jacket type offshore platforms are mainly fabricated from tubular steel members to satisfy the requirements of low drag coefficient, high buoyancy and high strength to weight ratio. However, utilization of these members generates high stress concentrations that are of major concern in fatigue life of offshore platforms (Jia, 2008).

The fatigue damage prediction may be principally performed using two techniques; namely the S–N approach and fracture mechanics (Shabakhty, 2011). The S-N method and the S-N curves are associated to a nominal stress approach, which relates a constant stress range, S, to the number of stress cycles, N, leading to the failure. The S–N curve is essentially obtained from empirical fatigue experiments. The nominal stress range for the location where the fatigue assessment is being conducted may need to be modified to account for local conditions that affect the local stress at that location. The ratio of the local to nominal stress is the definition of the Stress Concentration Factor (SCF). according to Miner's rule, fatigue assessment due to variable actions is normally based on the hypothesis of a linear accumulation of fatigue damage under constant amplitude stress ranges.

The second approach is based on fracture mechanics techniques, which describe the propagation of crack and its growth due to time-varying (tensile) stresses. Acknowledging the dominance of the S-N approach, fracture mechanics principles are best suited in situations where the normal S-N fatigue assessment procedures are inappropriate. For example, fracture mechanics has specific application in ancillary or supporting studies to develop an inspection plan followed by remedial actions (Kam, 1990).

This thesis presents a fixed jacket type offshore structure platform model for the prediction of fatigue degradation under hydrodynamic forces induced by wave action with due consideration of dynamic effects. The solution procedure is extended to a stochastic analysis in frequency domain dynamic response of fixed jacket offshore structures.

An analytical solution of fatigue analysis can be obtained through statistical analysis based on the assumption that the stress response of the structure is stationary, Gaussian, and narrow

band. However, the presence of the second peak per zero crossing due to local irregularities in a narrow band process causes the stress power spectra to become broad band, which means the spectral density covers a broad band of frequencies. Analysis of a broad band process requires a cycle counting algorithm in the time domain whereas the analytical solution is hardly utilised in this case.

Although time domain techniques are the most accurate in determination of stress power spectra, they are costly and time consuming. Simple methods for fatigue analysis can be developed if a proper balance between computational accuracy and physical realities can be achieved (Zienkiewicz et al., 1978). In this regard, it is desirable to simplify the statistical modelling based on the assumption that the load sequence can be ignored. This implies, for equal number of cycles, the equivalent (constant amplitude) stress range creates the same fatigue damage as the sequence of variable stress ranges that it replaces. The equivalent stress range can be obtained from the spectral parameters of a stress power spectrum (Chow, 1991). The concept works well for fatigue assessment even if the assumptions are not fully satisfied.

Frequency domain analysis is best suited for systems in random wave environments. The description retains the random nature as well as the frequency content of a real sea which means that it is able to realistically model the effect of wave frequency on applied wave actions and structural response. The response spectrum and its short term statistics is obtained using wave spectrum and the transfer function. In this approach water surface elevation is described by using a wave power spectra to account for nonlinear effects. The transfer function gives the steady state response of a system to a sine wave input and the dynamic characteristics of the system can be defined by measuring the transfer function over the entire frequency range.

Frequency domain analysis is usually applied in analyses of more moderate environmental conditions where wave statistics of the random sea is not altered (Etube, 1999). The main advantage of this method is that the computations are relatively simple and efficient compared to time domain analysis methods. For a motion analysis in the frequency domain, wave response analysis is performed for 55 frequencies (refer to Section 03.5), which is more than the 30 that is required by the codes (DNV, 2010).

Airy wave theory is used for low to moderate seas since the effect of drag forces on the local stress range is small. Linearization yields satisfactory results for structures that are exposed to small waves where nonlinear effects are negligible due to presence of inertia rather than drag dominated loading.

The significant wave height (*Hs*) and peak period (*Tp*) of a random sea-state should be specified for stochastic linearization to evaluate the linearized force vector. The linearization matrix could be obtained by minimizing the expected mean square error, considering the response to be Gaussian. The analysis is then performed by transforming the equilibrium equation into the frequency domain (Leira, 1990).

Methods reflecting free surface effects are expected to improve fatigue analysis. As an alternative this can be achieved by applying reasonable wave steepness, so the transfer functions automatically include the free surface effects (Vugts, 1978). For the determination of transfer function, the linearity demand can be relaxed to account for nonlinear (drag) wave loading by an appropriate selection of the wave height input.

The drag component of the hydrodynamic actions on the structure is also affected with the presence of a current. In addition to modifying the variable part of the wave action, this will cause a non-zero mean loading. However, for fatigue analysis the only concern is the range of applied action, which is much less affected than the peak action at the crest or the trough. Therefore, current forces can be ignored in fatigue analysis.

Marine growth affects platform added mass, member drag diameter and drag coefficient (API, 2007). This will increase the local and global wave loading on the structure and affects fatigue life of members. Both the drag and inertia term in Morison's equation should be increased to take the account of marine growth. The drag coefficient should additionally reflect the effect of roughness due to marine growth.

A marine growth profile is specified based on the thickness and roughness expected at the platform's site over the service life of the platform. The effect of marine growth on the hydrodynamic behaviour of members is included by increasing the member diameter in addition to adjusted drag and inertia coefficients.

The effect of nonlinearity depends on the amount that the structure is drag dominated (Skjong, 1991). Wave loading is nonlinear with wave height due to the drag term in the Morison wave load equation and free surface effects. In contrast, low to moderate seas are mainly inertial and require accurate assessment of the inertia coefficient for fatigue calculations (Vugts, 1978).

If the inertia forces are quite important, then dynamic analysis should be carried out either in frequency domain in which case transient effects will be neglected or in time domain in which case transient effects may be considered as well as non-linearity (Brebbia and Walker, 1979).

The influence of dynamic response on the long-term local stress range history is determined by using spectral analysis and a frequency domain dynamic solution.

The wave response method does not need any drag linearization (HSE, 2000). The type of wave theory depends on the procedure adopted. Since the hydrodynamic forces are essentially nonlinear, an iterative approach is employed. This precludes the requirement of performing a time history integration in a deterministic procedure on the assumption that an infinite train of a repeatable wave form has passed the structure with steady state response.

In the random approach, the repeatable wave is a wave train with the wave statistics model of the input wave spectrum or the surface profile input by the user. Therefore, the actual wave specified in the Sea-state input file is not critical if an accurate representation of the wetted surface is provided.

A sufficient number of steps (20 crest positions) are used to ensure that adequate member load segmentation occurs. The wave step yielding the highest degree of member segmentation and the greatest submerged length for each member is used by the program.

"*Sea-state*" module of SACS is used to calculate the hydrodynamic properties of each member and the wave kinematics are calculated by the "*Wave Response*" module. The wave elevation is modelled as a linear random superposition of regular wave components using information from the wave spectrum.

The effect of the structural motion on the relative water particle velocities can be accounted with an iterative approach to correct any nonlinearities. The distributed member forces are computed using Morrison's equation for each wave crest position. The equivalent joint forces are determined using static equilibrium and multiplied by the modal eigenvectors to obtain the modal generalized forces.

The generalized force is decomposed into various Fourier components to obtain the modal response. The structural motion at any point is then determined by summing the responses from all modes. As a result, the relative fluid velocity and a new set of member forces can be determined.

The generalized forces for current iteration are compared with the specified tolerance unless the maximum number of iterations is reached. The modal static values are obtained from the first iteration for one full cycle of the wave on the structure at rest position. The modal dynamic values are obtained from the iterative solution including the dynamic amplification factors.

Wave kinematics for every iteration can be recalculated to take account of structural displacement when using a relative velocity formulation. Since the displacements of the structure in the fatigue environment are usually very small to cause any significant loss of accuracy, wave kinematics from the first iteration can be used for all subsequent iterations.

Furthermore, relative velocity formulation of the Morison equation causes additional hydrodynamic damping that will reduce the wave loading. This phenomena does not occur for small structural displacements, which is the case for fatigue environment (ISO19902, 2007). Hence, the use of relative velocity formulation is ignored in the fatigue analysis.

Energy dissipation due to damping may have a profound effect on the structural response. If the forcing frequency is close to the natural frequency of the system, and the system is lightly damped, huge vibration amplitudes may occur. This phenomenon is known as resonance. The physical sources of damping are difficult to determine and to quantify with any certainty. A total damping value of 2% of critical damping is considered as the viscous damping coefficient that accounts for all sources of damping, including structural, foundation and hydrodynamic effects (ISO19902, 2007).

Most dynamic analyses of offshore platforms apply modal analysis techniques since they are efficient and reliable methods for calculating global structural responses. However, pure modal techniques are not accurate for local responses due to numerical inaccuracies involved in high frequency modes. In fatigue analysis the effects of both local and global dynamic responses are important to represent all significant dynamic responses in an accurate and efficient manner. Furthermore, fatigue analysis requires a very large number of modes to represent the local (quasi-static) member deformations accurately.

The modal acceleration method overcomes these aspects by superimposing dynamic responses onto a full static solution. This method allows for stress recovery with sufficient number of modes, so all dynamic and static responses are accurately included in the solution with computational efficiency. In any case, a modal analysis should also be performed to obtain natural frequencies and mode shapes of the structure to verify the dynamic behaviour of the structure.

Natural frequencies and mode shapes of the structure are obtained by using sufficient number of modes to verify that the dynamic behaviour of the model is realistic. The position of the platform natural frequency is reviewed to verify that it does not fall in the valley of the transfer function. A realistic range of natural frequency values should be considered, based on lower and upper bound values for the platform mass and stiffness.

Global transfer function plots are generated to verify that the specified waves are sufficient to accurately define the transfer function used in a spectral fatigue analysis. In order to accurately generate the peaks and valleys of the transfer function, a group of waves with frequencies around the primary and secondary modes of the structure are selected.

The mass matrix may be generated based on the lumped or consistent mass approach. Mass matrix created in the consistent approach includes off-diagonal coupling terms since the mass is distributed along the element. When including effects of fluid added or virtual mass acting normal but not tangential to the element, the element mass is not the same in all three directions; hence, a consistent mass approach is preferred.

Using a lumped (or diagonal) mass matrix for the structure's global response has a significant computational advantage in solving dynamic equations of equilibrium. However, local response of individual components shall be examined using a consistent mass model (ISO19902, 2007).

Dynamic characteristics (mode shapes and frequencies) of a structure are obtained by using the "*Dynpac*" module of SACS. Since linear theory (i.e. modal superposition) is used in dynamic analysis, non-linear foundations must be represented by the equivalent linear foundation model (pile stub). The PSI module is used to generate an equivalent foundation stiffness matrix for dynamic analysis using the centre of fatigue damage sea-state. The "*Pile*" module is used to determine length, properties and offsets for equivalent pile stub element based on pile head forces obtained from PSI analysis.

A Guyan reduction is performed to reduce the structural stiffness and mass matrices. The eigenvalues/eigenvectors for the master degrees of freedom are first extracted and then expanded to obtain the results for the reduced degrees of freedom.

Failing to account for the higher frequency harmonics in the wave force that are due to its non-linearity may cause potential errors in frequency domain analyses. However, for most frequency domain methods, equations of motion are solved by using linearized drag and inertia components, in which case higher terms are dropped for mathematical simplification.

The higher order terms in the dynamic analysis occur due to drag term, higher order wave theory and variable submergence of elements near the water surface (inundation or free surface effects). The basis for all simplified methods is linearization of the force vector in the matrix equilibrium equation and depend on the linearization procedure plus the load level.

Since high frequency modes react statically, the structural inertia load, which includes dynamic amplification can be mainly obtained from the low frequency modes. Likewise, hydrodynamic loading including the effects of structural motion is not affected by local structural motion, which is defined in the high frequency modes. Therefore, a direct solution technique can be used to represent the total loading on the structure.

In the direct solution technique the total loading on the structure is represented by equivalent static loading, which includes the inertia loads and the applied hydrodynamic forces. The inertia load is determined from the low frequency structural modes. The effect of structural motion is accounted for by the applied hydrodynamic forces. These equivalent static loads may then be directly solved to obtain stresses.

Equivalent static loading is obtained to generate the transfer function required in a spectral fatigue analysis. The solution files created include nominal stresses that are to be used by transfer functions. The wave data is specified in a sea-state input file based on the peaks and valleys of the global transfer function plots. A single pass analysis is to be performed (i.e. no iterations), which means that no relative velocity or acceleration will be included.

An equivalent static load case representing static and inertia loads was created for each of the 20 crest position of each wave. The wave is stepped through the structure using an 18-degree increment for 20 crest positions for a total of 360 degrees (one full wave cycle). A common solution file includes nominal stresses to create the transfer function. The same number of modes is to be considered in both Wave Response and Dynpac input files.

In “Wave Response” module the stress can be retrieved using either the equivalent static load method, an enhanced modal acceleration method or a modal acceleration method. However, the equivalent static load method is the recommended procedure for stress recovery.

A short term condition (stationary situation) of the sea, which lasts for a standard period of three hours is known as *sea-state*. Response statistics for each random sea-state is evaluated using hot spot stress transfer functions to incorporate the effect of wave frequency. Transfer functions are obtained as the response of the structure to a series of harmonic waves with a sufficient number of suitably spaced frequencies. A wave spectrum is used as the theoretical model of the sea-state to reflect the actual wave conditions at a particular time and location.

The long term model provides the most logical approach to design, especially concerning fatigue problems. Long term wave climate at a particular location is always empirical and cannot be defined by theoretical models since it is not stationary. The long term stress

distributions over the lifetime of the structure are obtained from probabilistic methods using statistical measures of the stress history. The stress transfer functions are the cornerstones of a probabilistic analysis, affecting the accuracy of calculated long term stress distributions (Vugts, 1978).

The wave statistics model consists of zero up-crossing periods, T_Z, significant wave heights, H_S, and their probability of occurrence to define the sea-state conditions during a long term period. The statistics of the original random process are assumed Gaussian, so they can be theoretically described. These assumptions are most applicable for low to moderate sea-states, which are the sea-states of interest in fatigue studies and create confused short-crested sea conditions (ABS, 2010).

The wave scatter diagram is used to represent the long term wave environment at a location during a year and is based on several years of site specific data to ensure realistic representation of the wave climate. This diagram specifies the probability density function of the joint occurrence of sea-state parameters, including significant wave height, a representative period and the mean wave direction. The method uses the wave spectrum to represent the range of wave frequencies existing in a random sea-state.

The long term fatigue calculation is based on the response spectrum, S-N curves and the scatter diagram where Rayleigh probability distribution function of the stress ranges is valid for narrow banded processes. Local stresses at connection discontinuities "*hot spot stresses*" are calculated using nominal stresses and stress concentration factors. Long term statistics of hot spot stresses is derived by accumulation of local hot spot stresses resulting from the variable loads.

S-N curves are used to define the fatigue characteristics of a material subjected to repeated cycles of stress with constant magnitude. The S-N curve delivers the number of cycles required to produce failure for a given magnitude of stress. Stress concentration factors are based on the level of detail in the model (Johansen, 2003) and determined based on the joint geometry and connection classification. Usage factors describe the rate of fatigue damage using Miner's law.

For fatigue calculations, the calibration process is conducted on Morison equation parameters, including drag coefficient, inertia coefficient and the wave steepness (Vugts, 1978). The application of probabilistic techniques to a fatigue analysis of offshore structures is discussed further in detail using the calibration process.

Chapter 2 Literature review

Literature review is conducted to identify the most appropriate design method and its significance meeting functionality, safety and economical aspects. Initially, the nature of the excitation forces with their effects on offshore structures are investigated in fatigue environment. Then, characterization of the fatigue environment is discussed with the objective of retaining the random nature as well as the frequency content of a real sea using spectral methods.

2.1 Environmental conditions

The performance and survival of offshore structures are mostly affected by environmental conditions including wave and wind action, currents and soil characteristics at the site. Long term deployment of offshore platforms necessitates proper consideration of fatigue both at the design stage and during maintenance for structural integrity assessment procedures. Fatigue loading on offshore structures is based on the wave loading regime, structural features and environmental conditions. Waves account for most of the structural loading and, as they are time dependent, produce dynamic effects that tend to increase the stresses and affect the long-term behaviour of the system. Wave-induced dynamic forces are one of the most significant forces leading to fatigue of offshore tubular structures. Furthermore, a structure's dynamic behaviour is significantly affected by the soil characteristics and the pile–soil interaction.

Estimating the fatigue damage of offshore structures is a complicated problem. When a structure is subjected to a long and complex random loading, power spectra representing different states of the load history are usually obtained from the structural dynamic analysis. The analysis usually relies on simple linear wave theories that assume sea elevations are stationary, Gaussian process and linearity of structure behaviour. The response of offshore structures to wave loading is of fundamental importance in the analysis.

If the stress response of structures can be assumed to be stationary, Gaussian, and narrow band, an analytical solution of fatigue analysis can be obtained through statistical analysis (Chow, 1991). However, if a narrow banded assumption is not valid, a correction factor is applied and the total fatigue damage is calculated through their weighted linear summation using Miner's rule (ABS, 2010).

2.2 Determination of wave forces

Determining the wave forces on a structure is difficult due to the nonlinear effects of water structure interaction (Azarhoushang, 2010b). Wave kinematics should be obtained by using the information on sea surface elevation and wave theory. This implies the calculation of the fluid velocities and accelerations in an undisturbed wave field with ideal inviscid fluid. Furthermore, hydrodynamic forces on a structure are derived by applying Morison's equation or the potential theory (Brebbia and Walker, 1979).

Hydrodynamic loading on large volume elements is governed by the potential theory; however, Morison's equation governs in the case of slender structural elements because these types of elements do not influence the flow field significantly. The two main lateral wave forces on offshore structures are the drag and inertia forces that are induced as water passes the individual members. The nonlinear quadratic drag term is proportional to the square of the fluid velocity and the linear inertia term is proportional to the acceleration of the fluid.

Morison's equation is empirical and was originally developed for vertical, rigid cylinders. It was then extended to the relative Morison equation for flexible structures to incorporate the nonlinearity in the drag term (drag damping). This extension incorporates non-linear effects of water particle velocity relative to the moving structure. Morison's formulation, which is used in the present study, remains the most commonly utilized method of relating water particle kinematics to hydrodynamic loading on the structure.

The higher order terms in the dynamic analysis occur not only because of the velocity-squared term but also due to higher order wave theory and variable submergence of elements near the water surface. The influence of the higher order term is negligible in low to moderate seas, which is the case of fatigue wave environments. In contrast, an accurate assessment of the inertial coefficient is of prime importance since fatigue environments are mainly inertial (Vugts, 1978).

Linearization is essential for most frequency domain methods and can be achieved by using a constant wave steepness (ratio of wave height to wave length) when selecting weight heights for the transfer function. This will provide a simple relationship between the wave height and the frequency; however, the wave heights selected should introduce a suitable level of nonlinear drag term (HSE, 2000).

The linear force vector can be evaluated by stochastic linearization, defining the significant wave height (*Hs*) and peak period (*Tp*) of a random sea-state. Assuming the response to be

Gaussian, the linear matrix is derived by minimizing the expected mean square error and the analysis is performed by transforming the equilibrium equation into the frequency domain (Leira, 1990).

Spectral analysis is a powerful method to capture the random nature of the environmental loads; however, it is based on some kind of linearization. The characteristics of the excitation can be modified by the response of the system. In other words, a system's response may approximate to Gaussian if it is a narrow band response derived from a broad band excitation. Hence, even though the excitation is non-Gaussian, the linearized spectral response is a Gaussian process. This will enable frequency domain techniques to capture nonlinear drag wave loading and free surface inundation effects. Enhanced frequency-domain linearization methods can be expected to be very practical tools for fatigue assessment since the response process could be realistically presented (Greeves, 1996).

Following the above, the wave heights used for determining the transfer functions must be selected in a suitable manner, so an appropriate level of non-linear (drag) wave loading is introduced. Constant wave steepness is commonly used for this, which provides a simple relationship between the wave height and frequency. Typical values of steepness are in the range 1:15 to 1:25. The actual value should be determined using a suitable calibration process for the actual structure and environment as described in this research study. The calibration procedure is developed using the Morison equation with adjusted parameters to suit the spectral analysis (Vugts, 1978). The drag coefficient, inertia coefficient and wave height are the variables that are calibrated for a given wave theory to produce similar force levels as conventional methods.

2.3 Forcing frequency and resonance effects

The structure's natural period and the wave spectrum's dominant period have a great influence on the dynamic response. The closer these two values are, the larger the response will be. Therefore, it must be ensured that the frequency of applied periodic loading will not coincide with a modal frequency to avoid resonance and large oscillations. Furthermore, to avoid unrealistic suppression of dynamic effects, the influence of global wave load cancellation should be investigated when structural natural period coincides with the cancellation point (Greeves, 1996).

For low forcing frequencies the response is mostly controlled by stiffness and tends toward the static response. The coincidence of forcing period (T) and natural period (T_n) is termed resonance (i.e., T_n/T is equal to 1.0). At this stage, the elastic and inertia forces are equal, so the motion continues if there are no excitation and damping. Subsequently, the structural response is greater than the static response depending on the damping ratio. As a result, the accuracy of a quasi-static analysis reduces and a dynamic analysis is essential for calculating the response in this regime. The structure reflects the waves entirely at the higher forcing frequencies and reversals are so rapid that inertia dominates (DNV, 2010).

The intensity of dynamic response is highly related to the natural period of an offshore structure. The first and second vibratory modes are usually lateral displacements at the deck level (surge and sway) out of which the higher mode is related to the less stiff direction of the structure. The third vibratory mode is usually a torsional mode. The ratio of dynamic response to static response is referred to as the *Dynamic Amplification Factor* (DAF). As shown in Figure 2-1 for the single-degree-of-freedom (SDOF) approach, DAF can be underestimated if the wave period is further away from the natural period (ABS, 2004).

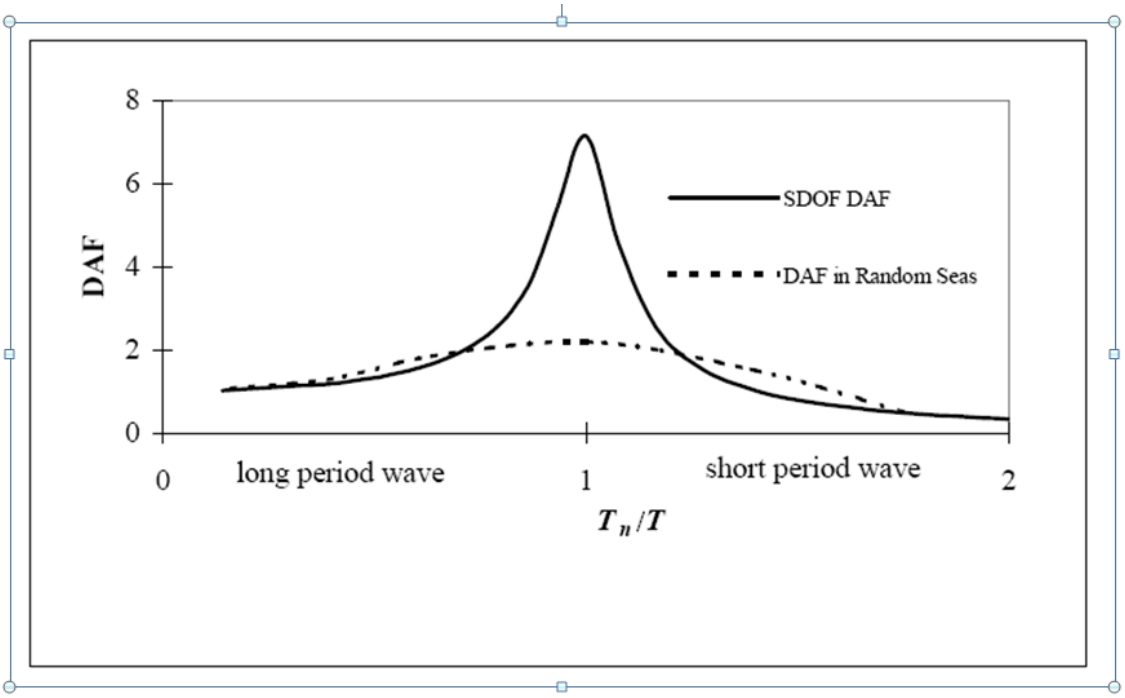

Figure 2-1 Resonance effects

2.4 Applicability of wave theories

Wave theories are classified as *small amplitude* or *finite amplitude* wave theories based on their formulas and boundary conditions at the surface of the wave (Ko, 1988). However, they all have symmetric crest and propagate without changing form. The small amplitude wave theory is referred to as linear wave theory and is often used in practice due to its simplicity. Since the motions are relatively small, higher order terms of wave amplitude are neglected to allow the linearization of the free surface boundary condition. Conversely, large or finite amplitude wave theories retain higher order terms, which applies to non-linear wave theories. For most applications where the ratio of water depth to wave length is not small, non-linear free surface effects in diffraction mechanics are generally negligible (Zienkiewicz et al., 1978).

Different wave theories may be applicable for the different wave height and period combinations used in the analysis. The applicability regions of wave theories are shown in Figure 2-2.

Fatigue damage calculation for offshore structures usually relies on simplifying assumptions on wave loads and the structural behaviour. As a common practice, simple linear wave theories are used where the sea elevations are assumed to be stationary, Gaussian process and the structure behaviour is assumed to be linear (Gupta, 2007). In this regard linear (Airy) wave theory is preferred in spectral analysis and normally could be used for all ratios of water depth to wave length (DNV, 2011). However, the linearity demand can be somewhat relaxed for the determination of transfer functions by an appropriate selection of the wave height input and suitable linearization of the results (ISO19902, 2007).

2.5 Wave action on offshore structure

Ocean based structures are mostly influenced by actions producing variable loads like waves and combinations of waves with other variable actions. If the loads are variable with time, they could excite dynamic response in the structure and intensify the fatigue stresses. This will cause degradation of structure due to cyclic wave loading, which leads to fatigue cracking and possible widespread fatigue. The static loads can be ignored in fatigue analysis. However, they must be considered in evaluating spring stiffness used to simulate piles. Since the pile load-deflection curve is nonlinear, appropriate spring stiffness for the low load levels associated with fatigue waves should be considered. Fatigue life of members and joints near the mud line are mostly affected with the boundary conditions of the model used to simulate the piled structure.

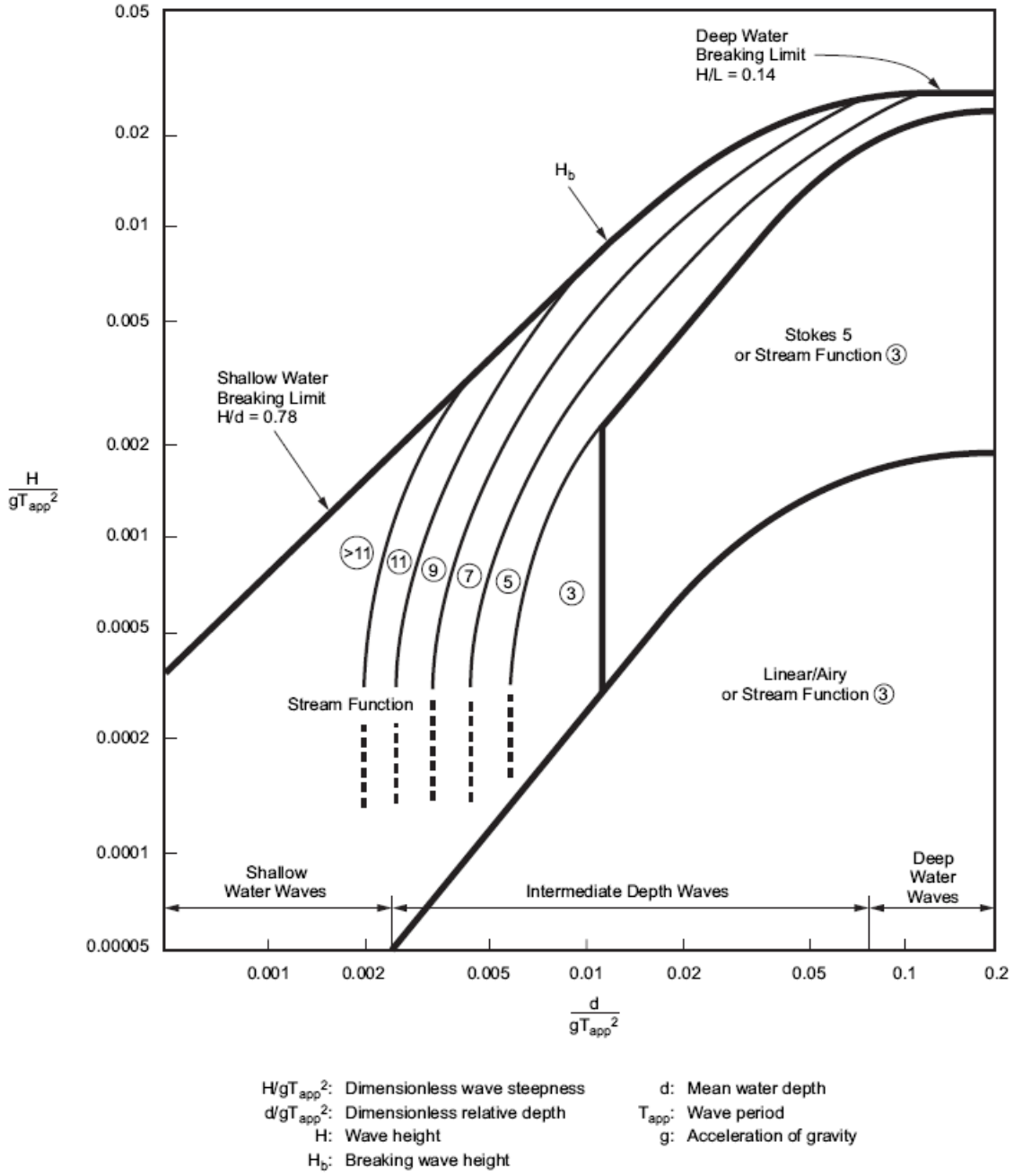

Figure 2-2 Regions of Applicability of Wave Theory (API, 2007)

Fatigue is known as a major mode of failure in marine structures, which respond dynamically to random wave and wind loading (Wirsching, 1987). Natural period of the offshore structure, shape and pick period of the wave spectrum, system damping and global wave load cancellation effects are considered as parameters influencing dynamic response. Where the first natural periods are in a range with significant wave energy to excite significant dynamic response, the dynamic structural response needs to be considered in the fatigue analysis. For

normal structure configurations and typical wave climates, dynamic response to waves can be ignored if the platform fundamental modes have periods that are less than 2.5 seconds.

In "quasi-static" method, dynamic effects into structural analysis is considered using a DAF for each global response parameter (e.g., base shear or overturning moment). DAF is the ratio of extreme dynamic response to the same response when dynamics is discounted. The hydrodynamic damping due to low waves is very small. Dynamic amplification increases in low damping systems when the period of the forcing function (the wave period) is close to the natural period of the structure and results in a fatigue-sensitive structure (Kinra, 1979).

The presence of higher harmonic components make the dynamic analysis more complicated, even for a regular wave in a frequency content of the wave forces on a structure caused by nonlinearity of the drag force, random nature of the wave, and structural or foundation nonlinearity.

Structural redundancy of a jacket type platform is low and a member failure in these structures cause immediate reduction of strength, which may result in catastrophic collapse of the structure (Golafshani, 2009). This will necessitate proper analysis technology to accurately account wave action on offshore structures. Steady state response of the structure to regular wave could be considered by methods based on mode superposition without the requirement for linearization. This will reduce the overall resonance effects predicted by the SDOF method due to the presence of higher harmonics. This method could be further extended for random seas using frequency domain methods provided that nonlinear effects such as P-delta, foundation stiffness, etc. are included in the method through suitable linearization.

Service loading of offshore platforms is mainly due to wave and wind action with variable amplitude and frequency content. The stochastic wave model accounts for the actual distribution of wave energy over the entire frequency range, which is the only method to simulate sea irregularity. The wave energy spectrum is characterized by the significant wave height (*Hs*) and average zero-up-crossing period (*Tz*) to represent a sea-state and is regarded as an extent of total energy distribution in a specific sea-state. For fully developed sea-states the Pierson Moskowitz wave spectrum is used, while for sea-states that are still developing, a Jonswap wave spectrum is preferred. The probability of occurrence of a particular sea-state is specified in a wave scatter diagram by *Hs* and *Tz*, which represents a composite of all wave directions and influences the stresses experienced. The stress spectrum is calculated by multiplying the wave spectrum by the square of the transfer function (Vugts, 1978).

The frequency domain method is well suited for systems exposed to random wave environments with moderate environmental conditions since the random response spectrum can be computed directly from the transfer function and the wave spectrum. The main advantage of this method is that the computations are relatively simple and efficient compared to time domain analysis methods. Long term effects should be specified for fatigue analysis to complete the definition of wave climate. For this purpose, the probabilistic description of the sea is defined by the wave scatter diagram that gives the probability of the joint occurrence of a particular *Hs* and *Tz*. The wave spectrum can be used to simulate the wave elevation as a linear random superposition of regular wave components.

Fatigue in offshore structures is regarded as a high cycle low stress incident. The response of a structure in moderate sea-states is of prime concern in fatigue damage considerations. In contrast, severe storms with return periods above 1 year are irrelevant since fatigue damage is mainly due to cycles with low stress ranges Hence, linearization is deemed to be acceptable. This will meet the requirement of spectral methods using transfer functions. If nonlinear effects exist, the ratio of response amplitude will no longer be proportional to wave amplitude and the transfer functions will depend on the wave amplitudes that are selected. In this case, suitable linearization is required to avoid ambiguous results.

However, there is uncertainty involved in the stress transfer functions due to actual wave loads on the structure, linearization of the wave loading, and local stress concentration factors (Vugts, 1978). The structural response of an offshore platform could be non-Gaussian after inclusion of nonlinear drag force and free surface effects in the wave kinematics calculations, even though the waves considered are linear and statistically Gaussian. An empirical modification around the free surface may be considered to account for free surface effects (Wheeler stretching).

Wave loads are variable loads acting on the structure and have the main contribution to fatigue damage. The annual variability of sea-states, spreading of wave energies around a dominant mean wave direction and wave directions relative to the structure are considered to be the basic components of the wave environment (Vugts, 1978). These elements should be selected such that the resultant forces and moments can be obtained precisely. Variable local stresses are derived from wave force calculations and affect fatigue life estimates.

The annual variability of sea-states can be defined by *RMS* (Root Mean Square) wave elevation, the mean period and the spectral width for the various sea-states at the structure's location. Hence, the wave environment can be described adequately. The first two parameters

are defined by a wave scatter diagram that gives the probability of the simultaneous existence of a particular significant wave height and zero crossing period. There is uncertainty involved in the spectral width, since in transforming from the time domain to the frequency domain we are forced to employ selective filters, which automatically reduce the effective bandwidth and therefore reduce the statistical reliability of the results obtained (Newland, 2012).

The spectral width reflects the irregularity of the sea. For infinitely narrow spectrum, the statistical distribution of all wave crests is given by a Rayleigh distribution of the peaks. The distribution function is more complex for broad spectral widths. Stress response is obtained using a user specified wave spectrum from site measurements or standard forms of the spectrum. The wave spectrum shape should represent distribution of wave energy with wave frequency in each sea-state. It is important to simulate the correct frequency content of a typical wave loading because crack growth of the structural steels in tubular joints is dependent of frequency content. Wave power spectra can be generally classified into two characteristic forms (Kam, 1992). These are related to either the fetch-limited, developing sea conditions without swell (e.g. JONSWAP spectra) or the fully developed seas (e.g. Pierson-Moskowitz spectra).

Furthermore, the long term wave climate description is determined using a wave scatter diagram by two parameters; the significant wave height (*Hs*) and the associated zero crossing period (*Tz*). Both of these parameters appreciably influence the stresses that are experienced. A wave scatter diagram specifies the probability of occurrence of waves coming from specific directions, which enables the cumulative effect of all of the wave conditions occurring throughout the platform life to be determined. Directional wave scatter diagrams that indicate individual sea-state probabilities for a number of mean approach directions are the most comprehensive form in which this information can be presented.

Wave loads on slender members (drag dominated structures) should be calculated using Morison's equation. A wide range of wave heights and periods are contributing to fatigue analysis. The majority of these are much lower and shorter than the design wave height and period for the strength analysis. The inertia term in Morison's equation is therefore much more important in fatigue analyses than for the strength analysis in an extreme storm condition, up to the point where the inertia term can become dominant over the drag term and the fatigue damage accumulation experienced is mainly caused by inertia dominated wave loadings (Jia, 2008). Consequently, due to small and medium sized waves, more member segments are required to properly define the distributed loading in fatigue analysis compared to extreme storm analysis.

The use of the relative Morison equation with its 'drag' damping reduces the response at resonance due to additional hydrodynamic damping from drag forces. For small structural displacements, which is the case in fatigue loading conditions, this additional damping is not observed in measurements; therefore, relative velocity formulation is not used in fatigue analysis (Frieze, 1997).

The drag forces due to joint contribution of wave and current cannot be calculated as a linear combination of their individual effects because of their nonlinearity. Therefore, the drag force is calculated for the resulting velocity of current velocity plus liquid particle velocity in the waves (DNV, 2011). However, for fatigue assessment, it is not the absolute value of the stress that matters but it is rather the stress range. Sensitivity analyses have shown that the influence of currents on the range of the calculated stress variations and hence on the fatigue damage accumulation in the structure is small and can be ignored.

Wave conditions in random sea-states are known to be short crested; i.e. the component waves are spread over a range of directions centred on the mean direction. An appropriate spreading function (e.g. cosine squared) may be used in conjunction with the wave spectrum to account for the effect of wave spreading on structural responses. However, experience shows that the effect of wave spreading is not significant in fatigue analysis and can be ignored.

In addition to wave environment, marine growth affects platform dynamics and fatigue life of members with increased local and global wave loading. Marine growth is a surface coat on marine structures that is formed by plants, animals and bacteria during the first few years after platform installation. Therefore, for new designs the maximum marine growth thickness determined for the site should be used for the fatigue analysis. However, marine growth profile could be considered to be the average thickness instead if the results are conservative (API, 2007). Marine growth increases hydrodynamic action, weight and added mass, which may influence hydrodynamic instability as a result of vortex shedding and possible corrosion effects. The effect of marine growth is accounted for by using an effective diameter for submerged elements in conjunction with adjusted drag and inertia coefficients for fouled members.

For dynamic analyses the foundation stiffness can have a large effect on the natural periods of the structure. A sensitivity of the theoretical period should be investigated to verify that it does not to fall in a valley of the transfer function. Fatigue sensitive members, especially in the base of the structure, should be investigated with the upper and lower bound foundation stiffness values. The stiffness values should reflect the foundation deflections and rotations in the

fatigue environment. For this purpose, the centre of fatigue damaged sea-state representing the wave conditions that contribute significantly to fatigue damage is used to develop the equivalent linear representations of the foundation stiffness.

The effect of wave action on appurtenances including conductors, caissons, risers, J-tubes, boat landings, fenders, launch rails, pile guides, pile sleeve assemblies, etc. are considered in their correct location and with their appropriate connection details to realistically transfer any loads on them to the structure. Miscellaneous attachments such as anodes also attract hydrodynamic actions. However, wave actions on anodes are distributed on the submerged structure and may be considered with an increase in the drag and/or inertia coefficients in the Morison equation (ISO19902, 2007).

Wave actions increase lateral loading and overturning moments of the structure, which can result in failure or possible collapse. Failure of primary structural members due to wave inundation mostly occurs in jacket-type platforms that have been designed to less stringent deck elevation requirements in shallow waters. The main causes of failure need to be addressed by reviewing current air-gap (the gap between the highest crest elevation for the design return period and the underside of the lowest deck level) standards that determine deck heights, as well as site assessment standards (Cruz, 2008).

There is no direct wave action on the topside structures supported by conventional jacket substructures provided that the air-gap requirement is met. However, for structures subjected to significant dynamic response (e.g. the elements span from the water surface to the deck without intermediate supports, like jacket structures with un-braced portal arrangements facilitating float over installation) cyclic wave loads on the substructure may introduce mass inertia forces in the deck, which result in significant fatigue loading of the topside structure. At this condition, fatigue of the topside structure should be performed for the combined substructure and topside system.

2.6 Hydrodynamic loading

Hydrodynamic loading on offshore structures are primarily composed of drag and inertia loading. Drag loading is caused by vortices generated in the flow as it passes the members and is more significant for tubular components of small diameter in waves of large height (D/H<0.1). Drag force is proportional to incident velocity squared and simply due to flow separation in viscose fluid (discounting the vortex shedding effects).

Inertia loads are caused by the pressure gradient and the local interaction of the structural member in an accelerating fluid and are most significant for structural components of large sectional dimensions ($0.5 < D/H < 1.0$). The inertia force, which is independent of any viscosity is composed of two parts; added inertia due to virtual mass of the member in motion and distortion of the streamlines around the stationary member.

Diffraction loading is a type of inertia loading that occurs when a structure modifies the wave pattern and is only significant when the sectional dimensions are greater than 0.2 of the wave length ($D/\lambda > 0.2$). The diffraction effect will be important for calculation of the air gap to the deck, wave loading on closely adjacent structures and drag loading on the towers and exposed conductors and risers of a gravity platform (Wilson, 2003).

Slam/slap loading is a local inertia force that occurs as a horizontal/vertical member passes through the water surface with a fluctuating buoyancy force due to the periodic immersion of the member. Since the force is applied impulsively, the dynamic response of the structure is of importance. It is recommended to allow for a pressure of 1 MPa on surfaces liable to slam or slap in exposed waters (Barltrop, 1991). Local inertia effects will be neglected when determining the global structure forces.

All slender members shall be investigated for the possibility of in-line and/or cross-flow vibrations due to vortex shedding resulting from the flow of water or air past the member, as appropriate. Vortex induced vibrations (*VIV*) causing drag amplification is considered for the global behaviour of the member (DNV, 2010).

2.7 Hydrodynamic analysis

Information on sea surface elevation in conjunction with a wave theory is used to compute the water particle kinematics. Furthermore, for a member with dimensions such that its presence does not significantly disturb the incident wave field, the in-line component of hydrodynamic loading is commonly evaluated by Morison's equation comprising of a nonlinear quadratic drag term that is proportional to the square of the fluid velocity and a linear inertia term that is proportional to the acceleration of the fluid.

This empirical equation was originally developed for vertical, rigid cylinders. Morison's formulation was later extended to include relative velocities term for flexible structures. If the structure moves, then the relative velocity modifies the drag force and can result in hydrodynamic damping. Relative acceleration results in a force that is similar to the inertia force, which can be most conveniently analysed by using the concept of an added mass of

water that is constrained to move with the structure or member. The non-linearity introduced by the drag force equation causes considerable problems in dynamic analysis. However, the higher order terms in the dynamic analysis occur not only because of the velocity-squared term but also due to higher order wave theory, variation in wetted leg length due to inundation effects, etc.

Despite the concerns raised, Morison's formulation, which is used in the present study, remains the most commonly utilized method of relating water particle kinematics to hydrodynamic loading on the structure. However, linearized drag and inertia components are used for most frequency domain methods. This will simplify the kinematic wave equation by dropping the high order terms, which will then be used in structural dynamic analysis (Greeves, 1996).

2.8 Global and local level approach

Fatigue damage is a highly localised phenomenon affected by local details in the structure. However, both the global loading on the structure and the local loading on individual members contribute to fatigue damage. In this regard a calibration process is developed, which is based on matching of global response parameters that are representative of the predominant fatigue loading. In certain situations, the structural design and assessment practices are based on component level whereas in certain other situations, a global level approach is necessitated (Rajasankar, 2003). All of these features must be correctly represented in the design process.

The hydrodynamic load comprises of in-line forces (i.e. forces in the wave and current direction) as well as transverse forces (i.e. forces normal to the wave and current direction). Transverse forces are neglected in the global analysis; however, they may cause vortex induced vibrations of individual legs, which has to be investigated as local checking.

Both type of the above forces have nonlinear interaction with fixed jacket type offshore platforms with slender elements. The in-line forces are the most important and are modelled by the extended Morison equation. In extreme wave situations, the quadratic drag term of this equation is the dominating term, which leads to a further increase of the extreme forces with severe consequences for the dynamic response (Karunakaran, 1995). However, the experienced fatigue damage accumulation is mainly caused by inertia dominated wave loadings due to small and medium sized waves.

Modal analysis techniques offer an efficient and reliable method for global structural response. A lumped mass model in modal analysis is adequate to be used in global structural response. If the mass of the structure is lumped at the nodal points, only the translational degrees of freedom is associated with mass. If a lumped parameter model is used, both for mass and loading, all rotational degrees of freedom, except at the base point may be eliminated by simple static condensation without introducing additional constraints on the model. This reduced model is a realistic proposition for even quite extensive parametric studies. However, it does not always adequately predict local dynamic response.

For fatigue analysis, we should accurately represent the local (quasi-static) member deformations. In this regard local responses shall be examined using a very large number of modes and consistent mass model. Disregarding three-dimensional effects (free surface), the added mass can be taken as being equal to the mass of the water displaced by the cylinder. It is found that the effects of the free surface will generally reduce the added mass and thus tend to increase the natural frequency of the structure.

2.9 Probabilistic versus deterministic methods

Frequency domain analysis is carried out by either deterministic or probabilistic methods. The deterministic approach is based on the height exceedance diagram while the probabilistic approach is based on the spectral curves of wave height (Brebbia and Walker, 1979). When the structural natural periods and the wave periods with significant energy are well spaced (i.e. when the structure does not respond at its natural period) a quasi-static behaviour is expected and the deterministic method of analysis is usually appropriate. This quasi static behaviour permits the dynamic amplification factor to be calculated by simply considering the dominant waves in the sea (Barltrop, 1991). However, it is recommended to account for the randomness of the loading and resulting responses.

Determination of local stress history depends on whether the fatigue design approach is deterministic or probabilistic. In a deterministic analysis, the total number of stress variations is the same for all points of the structure and equal to the total number of individual waves. In reality the number of stress variations changes from one point to another in the structure and neither of them is equal to the number of waves. This necessitates a probabilistic approach to reflect these properties in a random wave environment (Vugts, 1978).

In the deterministic approach, fatigue wave environment is defined using periodic (regular) waves, within which neither the random nature nor the frequency content of real waves are

reflected. Hence, the deterministic procedure, which produces a deterministic short-term distribution of the stress range for each sea-state is not suitable for dynamically sensitive structures. However, this approach is recommended for fatigue assessment of structures that are not fatigue sensitive, as well as during the initial design phases for screening purpose only (ISO19902, 2007).

To retain the random nature as well as the frequency content of a real sea, spectral methods should be used in the probabilistic approach. In the spectral analysis method, a sea- state (the short-term wave environment) is represented by a wave frequency spectrum to allow a probabilistic determination of the stress range (short-term distribution) for each sea-state and at each location of interest in the structure. This procedure is appropriate for final fatigue assessment, especially for dynamically responding structures. The disadvantage is the requirement for linearization of the hydrodynamic drag action, wave inundation effects and foundation behaviour in global analysis, by which the nominal stresses are determined.

Since environmental loads are random in nature and many of the fatigue design factors are subject to considerable variability, the probabilistic approach seems particularly relevant with no reliable link to the deterministic methods. Only the variable part of the local stresses is considered in the probabilistic approach, where both the magnitudes and the number of cycles of the long term stress response are affected (Wirsching, 1980).

2.10 Fatigue environment characterization

It is important to distinguish between the short-term and long-term descriptions in characterizing the fatigue environment. In the short-term description, the sea-state is considered stationary over a short time period and the variation of the short term statistics over a longer time scale (e.g. over the life time of the structure) is considered as long-term description in fatigue analysis (Iraninejad, 1988).

A short term sea-state is characterized by a significant wave height and a zero up-crossing period. For dynamic wave analysis, the structure is analysed for a range of frequencies at unit wave amplitude to obtain the structural transfer function. The transfer function is combined with the wave spectrum to evaluate the response spectrum. The statistical properties of the response can be found by standard spectral analysis techniques (HSE, 2000). For a zero-mean Gaussian process, extreme values are evaluated with a Rayleigh distribution of the peaks.

Statistical modelling under random loading is simplified by a linear damage accumulation assumption. This assumption simply states that the stress cycle interaction effect in the load history is negligible and therefore the fatigue damage due to a variable amplitude stress history can be evaluated as the linear summation of the damages caused by individual cycles. Therefore, the equivalent stress range can be determined by the probability density of stress peaks of equation (Chow, 1991). Short term statistics are weighted by the product of the probabilities of occurrence of the sea-state and the wave approach direction. Then Long-term statistics are obtained by accumulating the weighted short-term statistics over all sea-states in the scatter diagram and over all wave approach directions. From the cumulative distribution, the number of occurrences in discrete stress range blocks are calculated and used as input for the fatigue damage calculation. An example of a long term cumulative distribution of hot spot stress ranges and its subdivision into stress range blocks is shown in Figure 2-3. Fatigue calculations are based on the assumption that a single-slope or bi-linear SN-curve is used (Johansen, 2003).

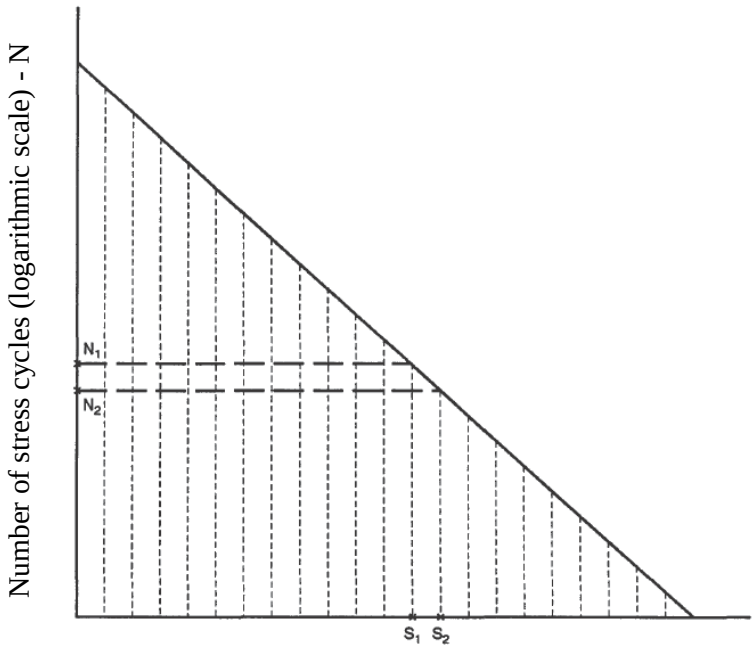

Figure 2-3 Typical long term cumulative distribution of stress ranges

Chapter 3 Analysis

In this chapter an analytical solution of the fatigue assessment is presented through statistical analysis which suits a random process. The methodology used here is a frequency domain analysis using spectral density functions and the transfer function approach to model the response spectrum. This approach is useful to handle nonlinear effects while the wave statistics of random sea is not changing due to existence of short periods in fatigue loading environment and water surface elevation can be properly described by wave power spectra.

The realistic distribution of wave energy over the relevant frequency range is suitably accounted for using spectral analysis. The structural model is considered in sufficient detail and the applicability of analysis method to dynamically responding structures under random nonlinear wave loading demonstrated as a relevant response tool.

3.1 Model definition

SACS software is used to model the linear and nonlinear behaviour of the system. A jacket type offshore platform model is developed for dynamic fatigue assessment. The structural model is considered with an appropriate three dimensional distribution of the structure's stiffness including the topside, the jacket and its foundation to reflect all relevant characteristics of the structure as shown in Figure 3-1. The plan and elevation views of the jacket structure is presented in Figure 3-2 to Figure 3-9.

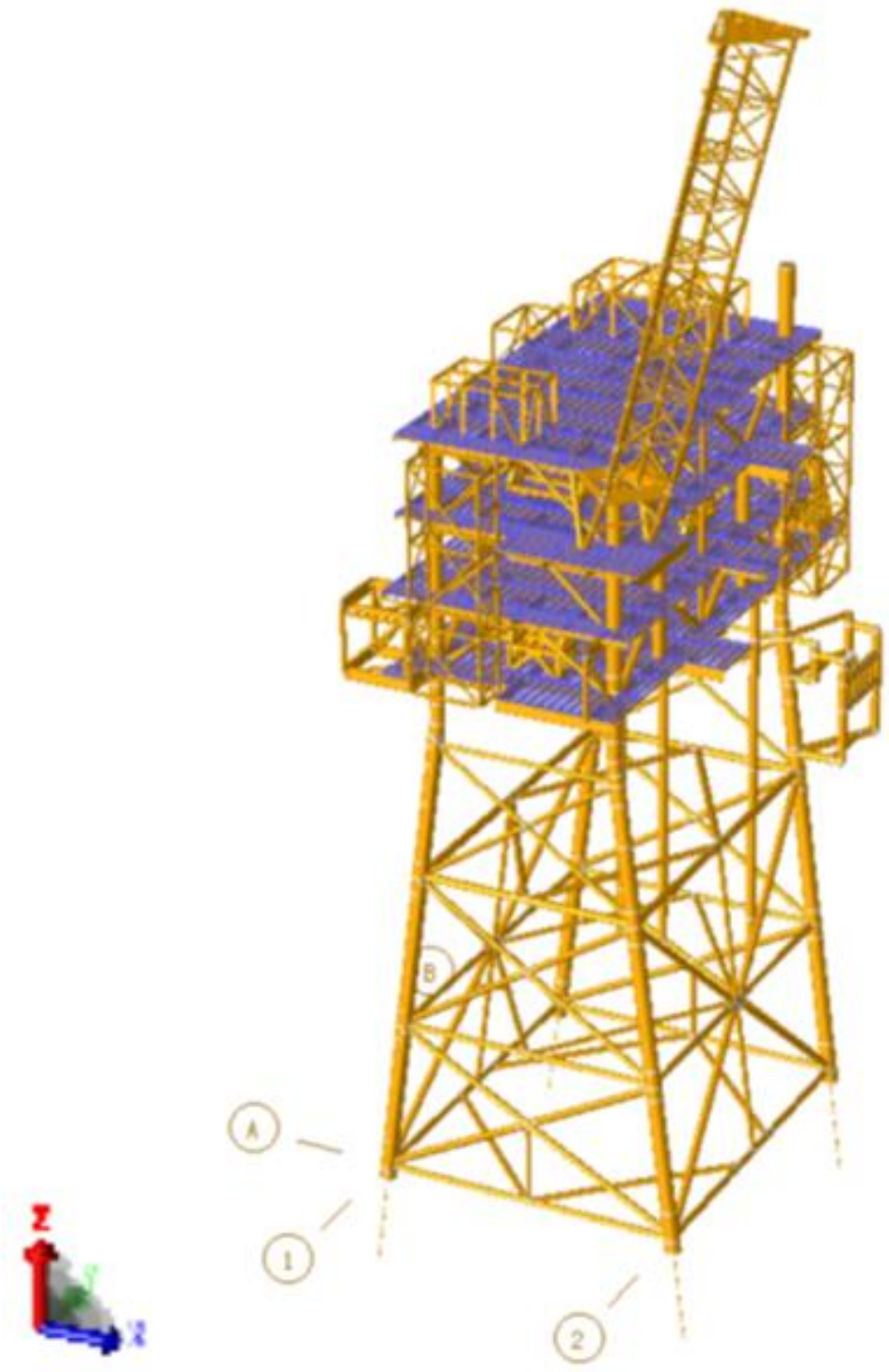

Figure 3-1 General View of SACS Structural Model

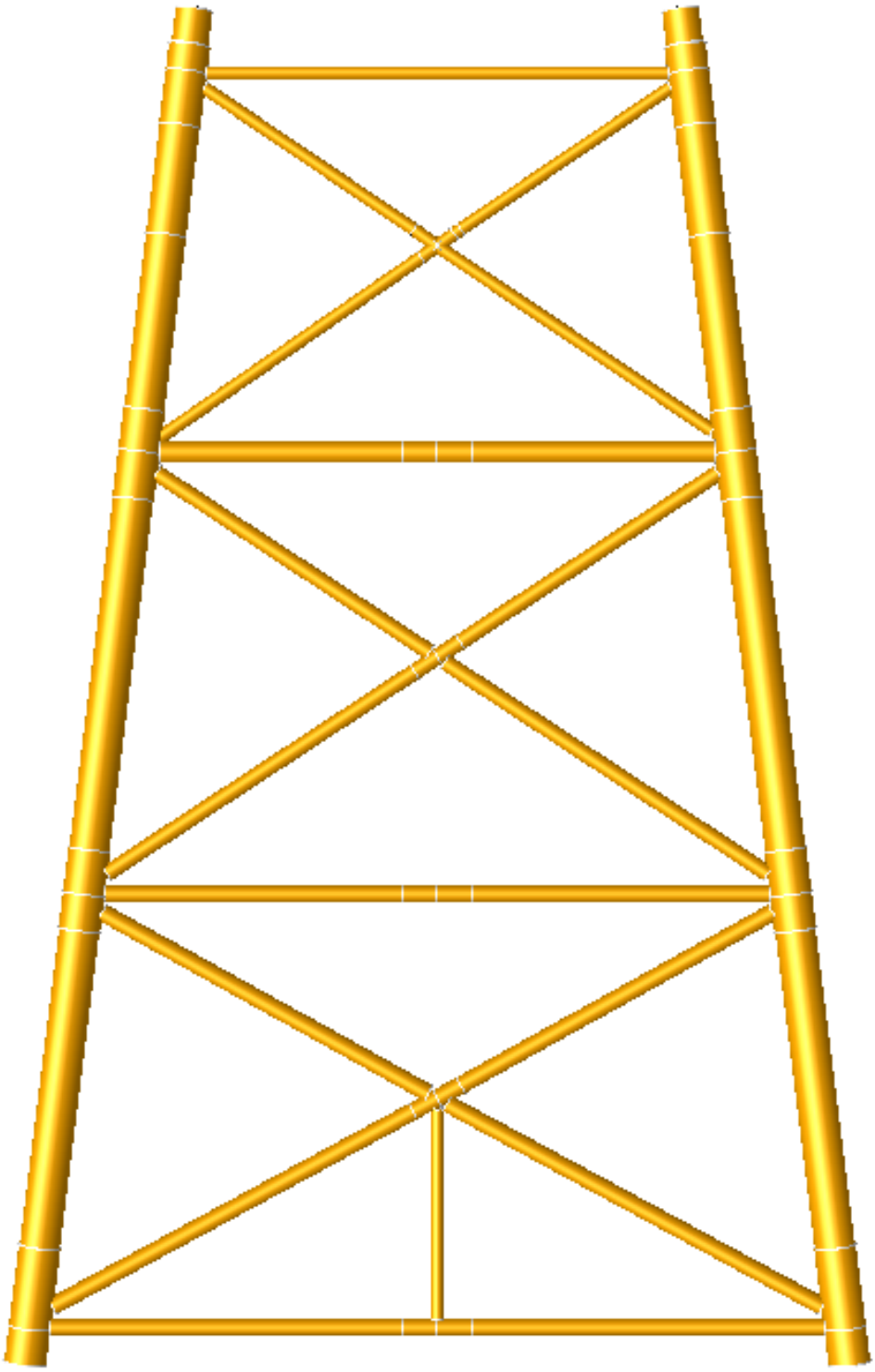

Figure 3-2 Face Row A

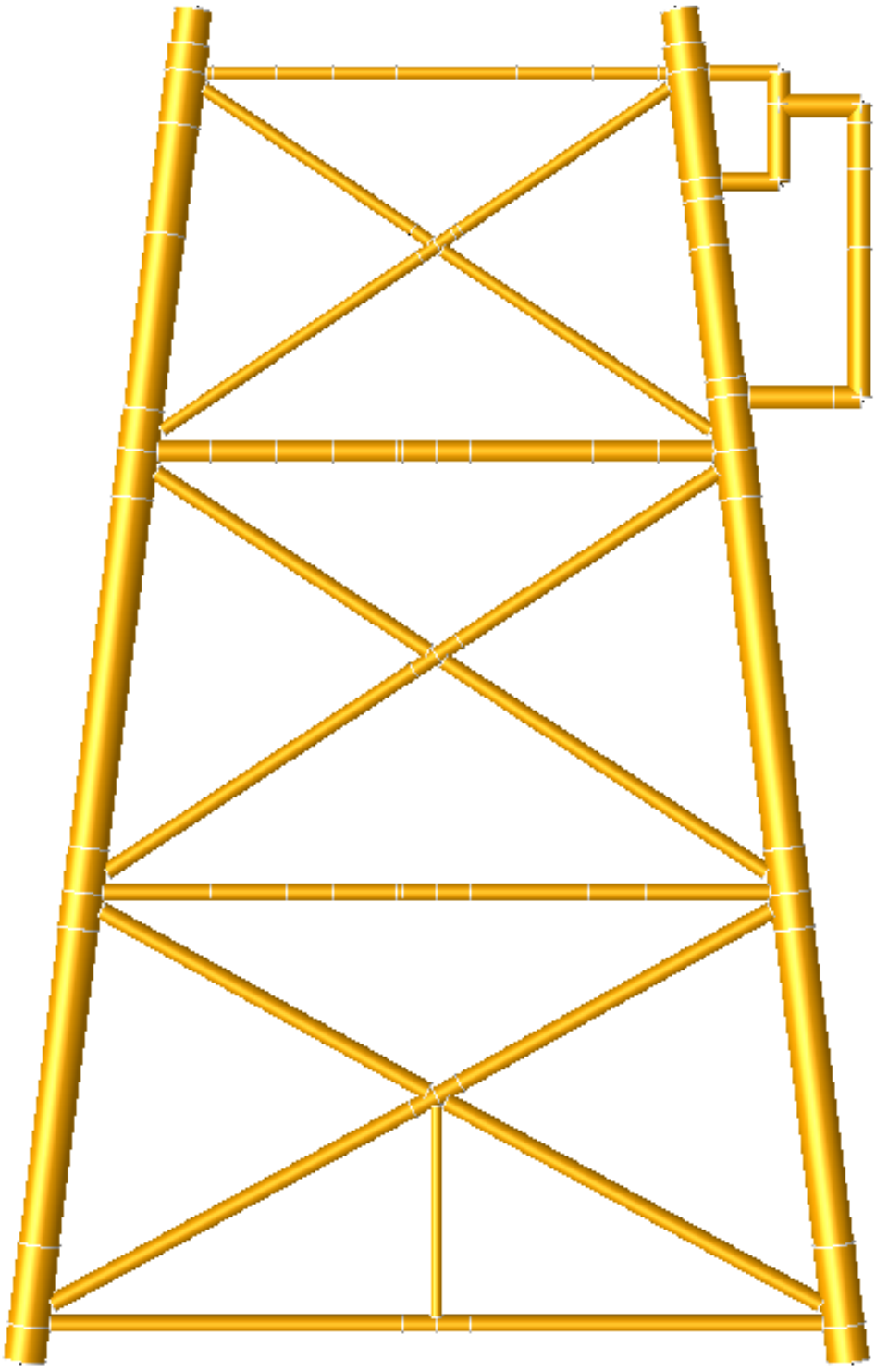

Figure 3-3 Face Row B

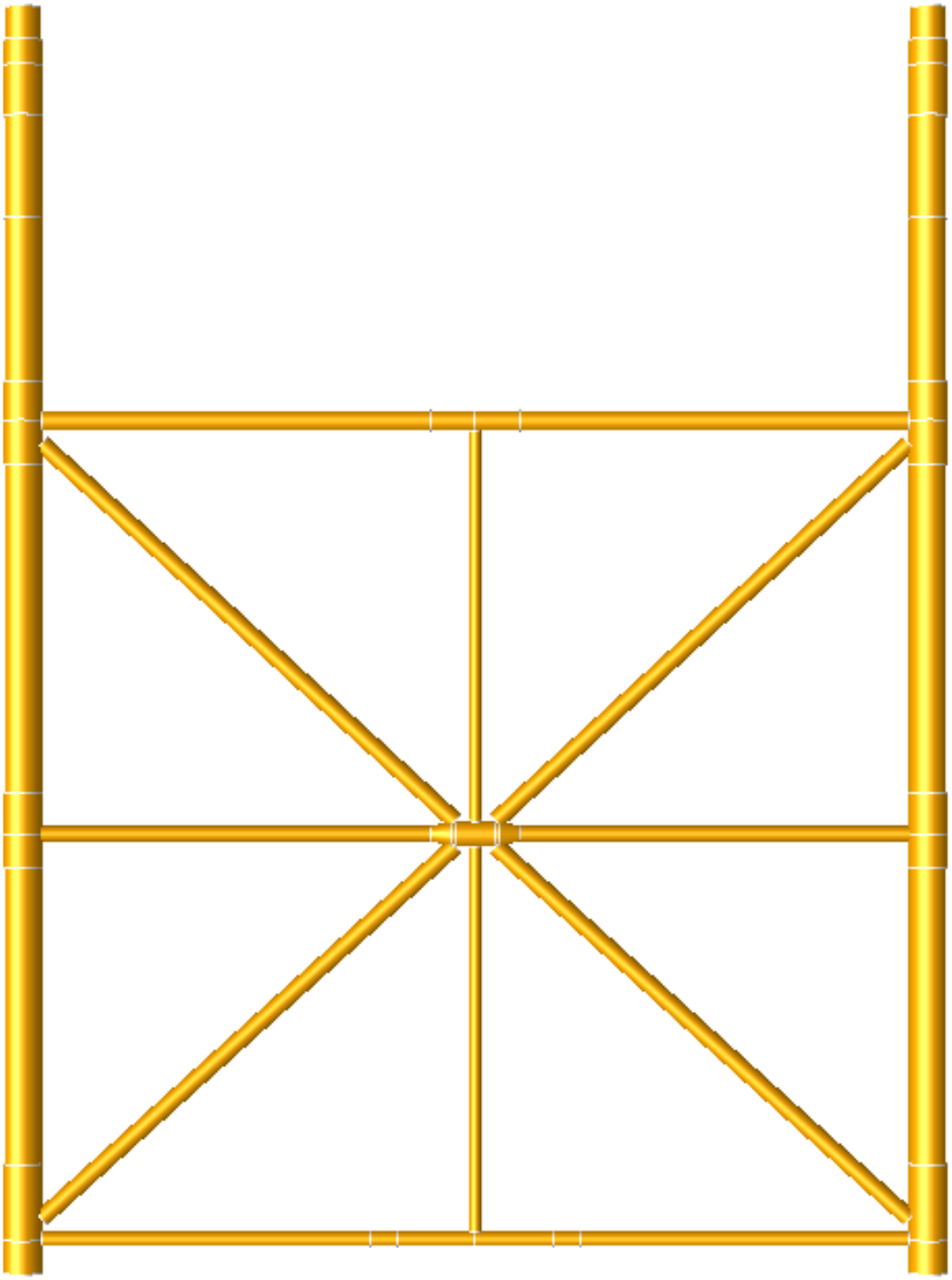

Figure 3-4 Face Row 1

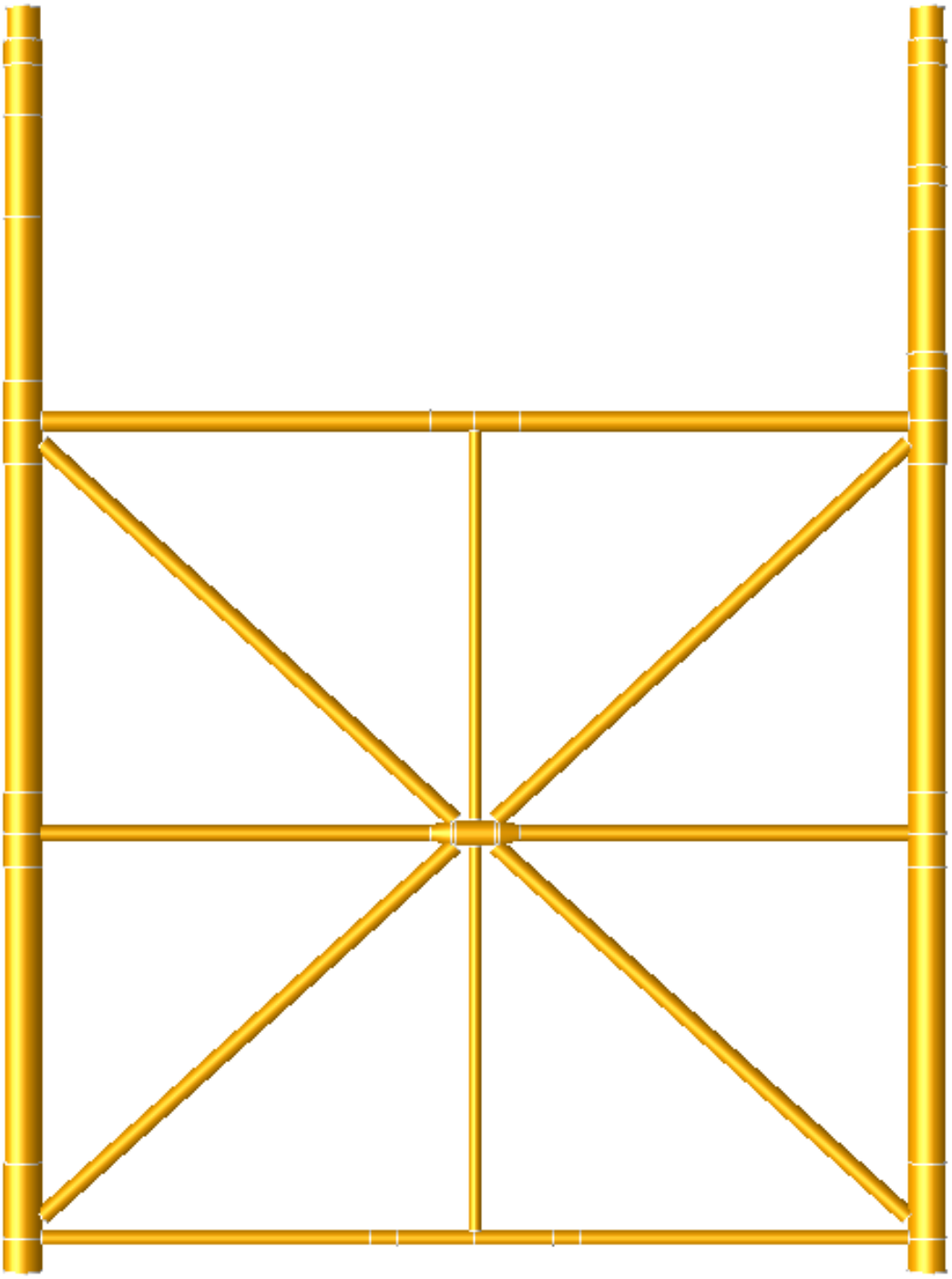

Figure 3-5 Face Row 2

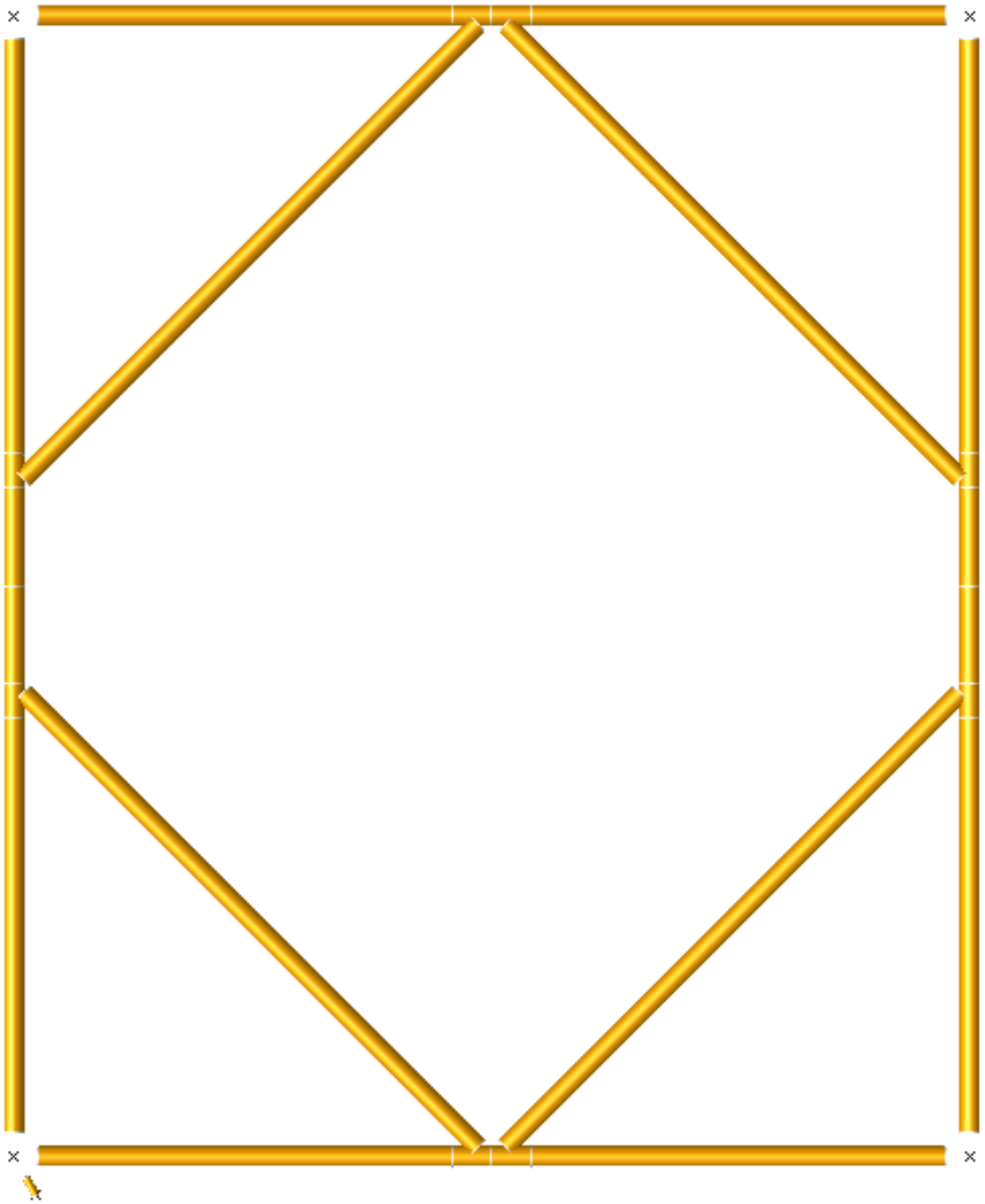

Figure 3-6 Plan at -41.285

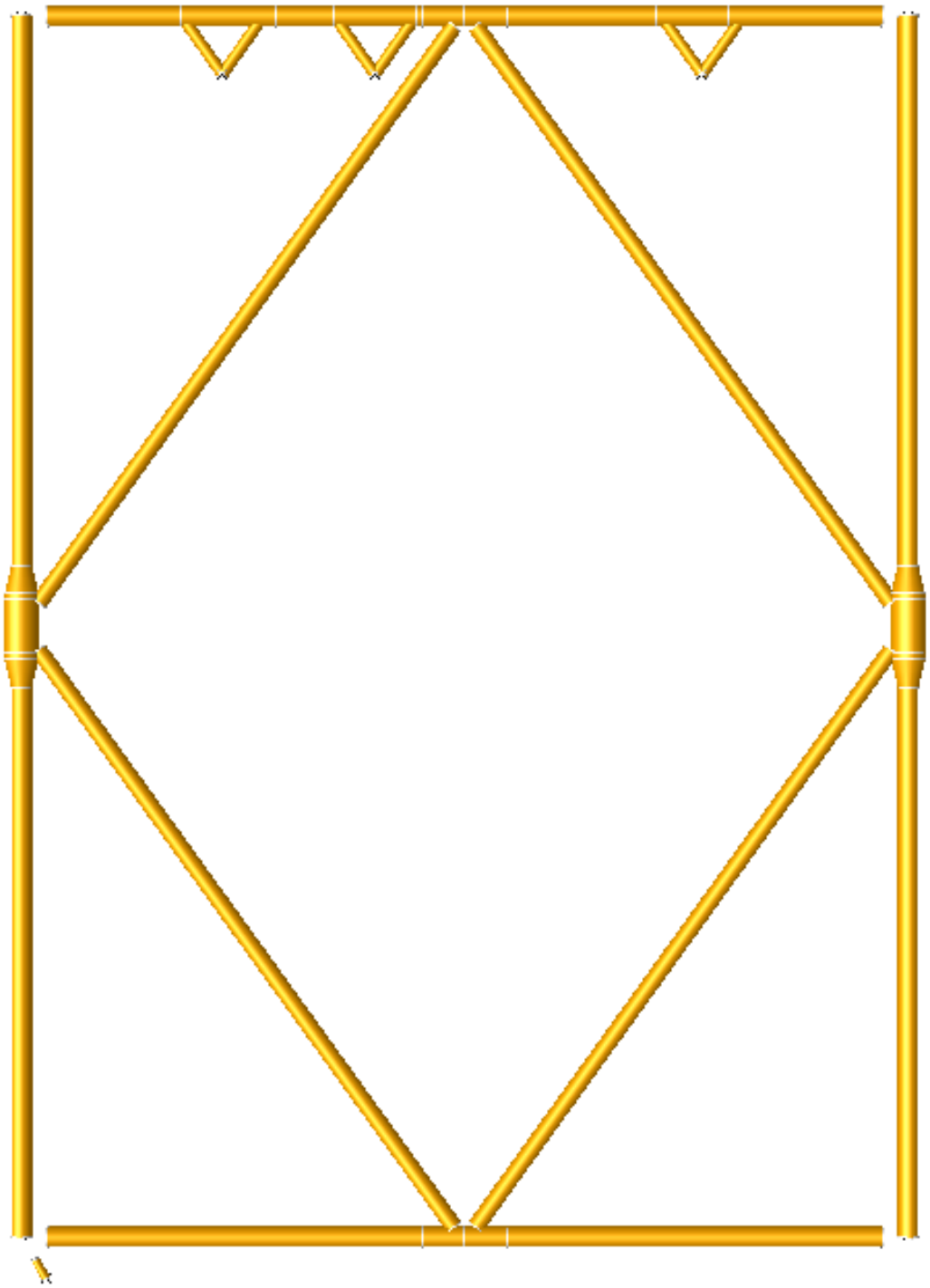

Figure 3-7 Plan at -25.3

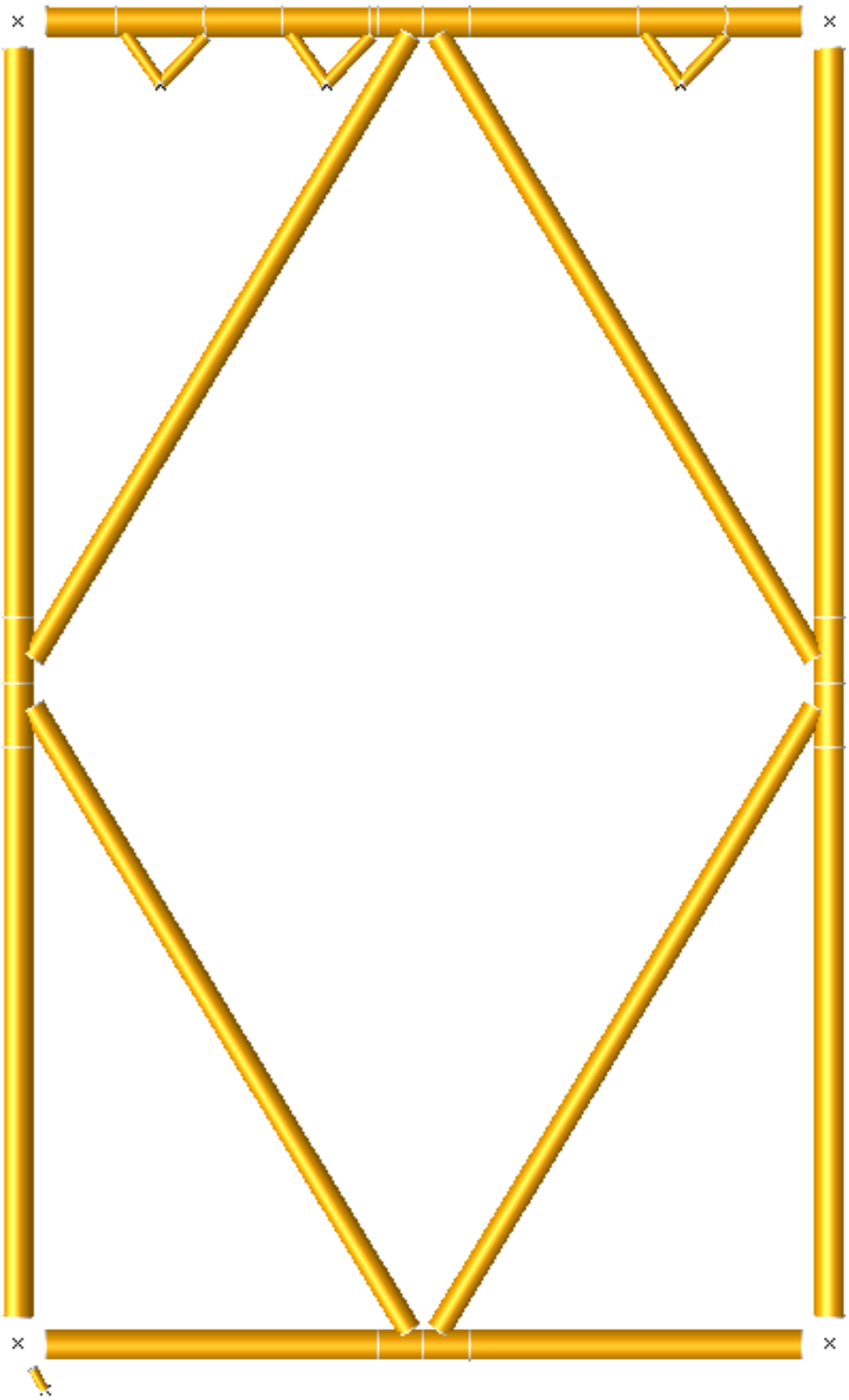

Figure 3-8 Plan at -9.0

Figure 3-9 Plan at 5.0

The space frame structure consists of beam elements and the member intersections are modelled such that the resulting nominal member end stresses are consistent with their subsequent use in the fatigue analysis. In this regard, nominal brace stresses are normally computed at the intersections of the brace and chord centrelines except for large diameter chords or short braces. Later, more refined modelling is considered at the local joint geometry by offsetting the brace member to the face of the chord.

The model does not account for stress raising effects due to geometric discontinuity of the welded joints. However, these effects are incorporated using *Stress Concentration Factor* (*SCF*). The design hot-spot SCF can be obtained by the finite element method, by parametric equations or from standard references.

The mass model includes all structural elements, miscellaneous attachments, marine growth, entrapped water and added mass using a consistent mass model to incorporate local dynamic response for fatigue assessment. For stiffness modelling, half of the corrosion allowance is considered when determining the wall thickness of members to represent the average condition during the life of the member. Main characteristics of this jacket and environmental data are listed in Table 3-1.

Table 3-1 Platform General Data

Jacket dimension at mud line (EL -41.3 m)	30.15 (m) × 36 (m)
Jacket dimension at work point (EL 7.3 m)	18 (m) × 36 (m)
Upper Deck dimension at EL 35.5 m	41.2 (m) × 23.2 (m)
Lower Deck dimension at EL 13.3 m	51.6 (m) × 23.2 (m)
Topside Operating Weight	1140 (MT)
Water Depth	42.72 m

The fixed jacket platform considered is supported by four legs. The analysis is performed for a water depth of 42.72 m corresponding to Mean Sea Level (MSL). The wave scatter diagram is used to represent the long-term statistics of the sea-state. The effect of wave frequency on wave loading and structural response is accounted through the use of hot spot stress transfer functions. The platform has four topside levels with a topside operating weight of 1,140 tones. The topside was installed using the *float over* method, so there are no braces at sea water level bay in the Y-direction and portal action is considered in this direction. The first two natural periods of the structure are 3.37 in the Y-direction and 1.90 in the X-direction, which are sway modes. The next mode is a torsional mode with a natural period of 1.37 seconds.

Frequency domain methods are generally applied to linear models; therefore, linearization of the foundation stiffness is performed at a suitable response level such that the foundation deflections and rotations are correctly reflected using the centre of fatigue damage sea-state. This will yield a lower response level compared to extreme sea-state and a correspondingly stiffer foundation, which is appropriate for fatigue analysis. For this purpose, a pile super element (pile stub) is developed within the pile solution module of SACS that yields the same deflections and rotations as the soil-pile system. Two files are used for the pile analysis, including structural input file and the PSI input file (refer to A.7).

Soil behaviour is simulated in the PSI input file by using the lateral and axial soil resistance deflection data (T-Z, P-Y, Q-Z) of the soil strata along the length (67.5 m) of the pile. The cyclic P-Y curve is used to properly simulate cyclic laterally loaded pile behaviour. Hence, the effect of cyclic loading on soil stiffness is considered in the assessment. The pile stub has the same properties as the pile (1.37 m diameter, 0.05 m thickness), but the relative equivalent length is much smaller and ranges from "4*D*" to "10*D*", where "*D*" is the pile diameter (1.37 m).

Non-linear behaviour of a piled foundation arises from non-linear characteristics of the soil, finite deflection of the pile (P-δ effect) and yielding in the pile. The nonlinear functions that define the cyclic soil behaviour vary from quasi-elastic at deep regions to strongly non-linear curves near the mud-line, which exhibits a complex plastic behaviour. Therefore, only the first soil layers are remarkably non-linear (Lima, 1985).

Due to non-linear behaviour of the pile-soil system, the structure-foundation stiffness is a function of displacement. In a linear analysis, the structural stiffness matrix is based on the undeformed structure and does not change as the structure deforms. However, due to the non-linearity involved, the stiffness matrix for the deformed shape cannot be determined until the deformed shape is obtained. The deformed shape, in turn, cannot be found until the stiffness matrix is found. Iterative methods have proven to be useful for solving this type of problems.

The soil-structure interaction considered in the research subject combines a linear analysis of the structure with a non-linear analysis of the piled foundation. The piles are represented by a linear or beam-column formulation and the non-linear soil (T-Z, P-Y and Q-Z curves) by piecewise linear springs at the *decoupling point* at the leg base; where there is no coupling between rotations and translations. This soil model implies a hysterical behaviour of the soil-structure interaction (Karunakaran, 1995). The solution involves "condensation" of the structural stiffness matrix to connection nodes at the pile heads, a non-linear iterative solution

of the foundation and structure to determine the pile head displacements and back-substitution of these displacements into the reduced equations of the structure to determine the displacements throughout the structure.

The process of condensation involves reducing the linear structure above the pile-head joints and loads to an equivalent linear stiffness matrix involving only the pile-head degrees of freedom and a set of forces applied to those degrees of freedom. Both the finite difference and finite element methods are used in offshore structural analysis programs to incorporate piled foundations characteristics.

A structure's dynamic behaviour is significantly affected by the soil characteristics and the pile–soil interaction. Since the natural period(s) of the structure is highly affected by the foundation stiffness, upper and lower bound foundation stiffness values are examined to avoid coincident of theoretical natural period with the cancelation point on the transfer function, which suppress the dynamic effects. Fatigue Demand is stated in terms of stress ranges that are produced by the variable loads imposed on the structure. This will require an appropriate structural analysis with due consideration of the boundary conditions (i.e. soil-structure interaction). It is now generally accepted that soil-foundation interaction is important and should be taken into account when calculating the response of the system. How important it is will depend on the particular soil and structure under consideration (Brebbia and Walker, 1979).

Analytical representations of the fluid-structure interaction are complicated due to the drag term and free surface effects. However, it is possible to approximate the influence of non-linear wave actions on the calculated stresses by an appropriate selection of the wave height input and suitable linearization of the results (ISO19902, 2007).

The modelling of the structure presents modest difficulties in comparison with an adequate description of the sea and the soil. Since prediction of structural safety and serviceability is the objective of the analysis, the structural response is of primary concern with due consideration of surrounding media, sea and soil. The thesis is a state of art report, describing a modelling that reflects present knowledge of physical properties, computational capabilities and economical restraints.

3.2 The basics of random process

For a zero-mean Gaussian process the spectral method is performed in the frequency domain analysis using structural transfer functions with appropriate spectral density functions (wave spectrum) to obtain the response spectrum and its statistical properties such as the standard deviation, zero-crossing period, etc. The frequency response function $H(\omega)$ gives the steady state response of a system to a sine wave input. By measuring $H(\omega)$ for all frequencies, we completely define the dynamic characteristics of the system. The need for measuring the dynamic characteristics of a system by monitoring its response to a random input signal arises from the idea that if these characteristics are known, then the operating conditions of the system can be optimized, so it runs at peak performance (Newland, 2012).

Spectral analysis is a practical method that is best able to represent the random nature of the wave environment and explicitly accounts for the influence of the frequency of excitation (the wave frequency) on actions as well as on the structural response. The method is applicable only to a linear system subjected to random excitation with simple form of input—output relations for spectral density. However, by suitable linearization of non-linear elements in the problem formulation (principally the drag term and wave surface effects around the still water level), this formal constraint can be adequately overcome as it is based on superimposition of many individual frequency components only applied in the analyses of moderate environmental conditions (i.e. fatigue analysis) where linearization gives satisfactory results. In a moderate environment (stationary random process), the statistical characteristics of the random sea does not change with time due to the existence of short periods. Therefore, we can obtain the probability density function for a random process $p(x)$ during the time interval T as presented in Equation 3-1.

$$P(x)dx = \frac{(dt_1 + dt_2 + dt_3 + \cdots)}{T} = \frac{\sum dt}{T} \qquad \text{Equation 3-1}$$

If x is a random variable with a mean value of $E[x]$ and standard deviation of σ, the variance, σ^2, is as defined in Equation 3-2.

$$\sigma^2 = E[(x - E[x])^2] = E[x^2] - (E[x])^2 \qquad \text{Equation 3-2}$$

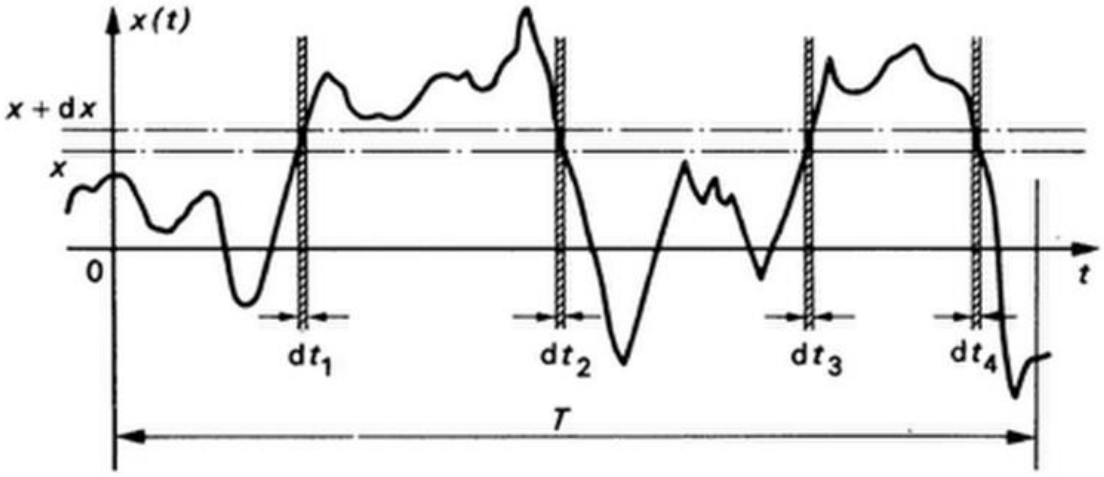

Figure 3-10 Probability density function p(x) for a random process

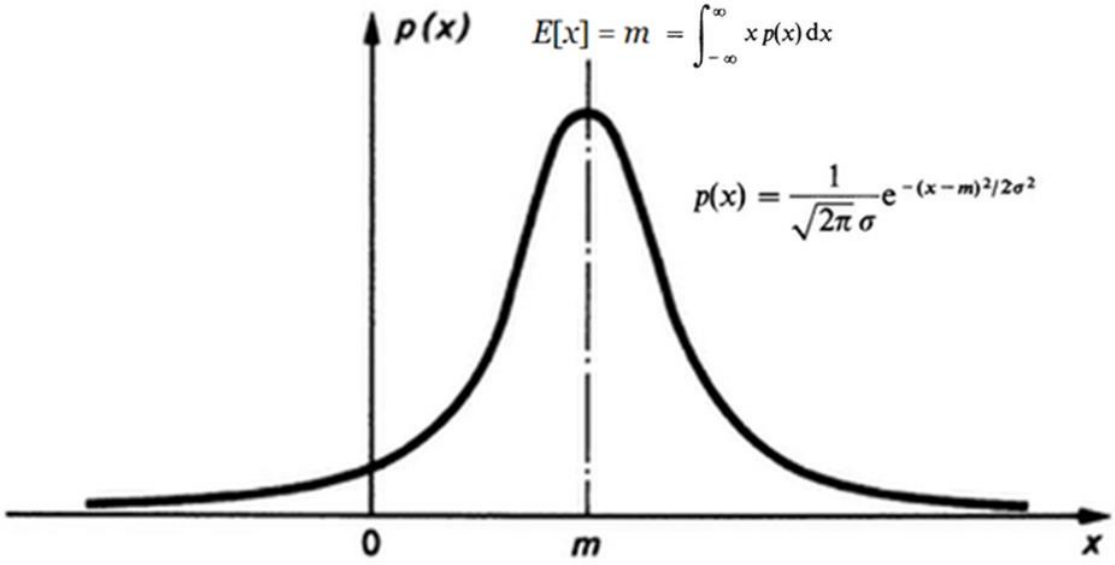

Figure 3-11 First-order probability density for a normal (or Gaussian) process

Random variables of x and y with mean values of m_x and m_y are statistically independent (non-correlated) if the normalized covariance ρ_{xy} (correlation coefficient) as defined in Equation 3-3 is zero.

$$\rho_{xy} = \frac{E[(x - m_x)(y - m_y)]}{\sigma_x \sigma_y} \qquad \text{Equation 3-3}$$

The probability distribution function is used to describe the distribution of values of a random variable, and defined in Equation 3-4 as the shaded area under the probability density curve.

$$P(x) = \int_{-\infty}^{x} p(x)dx \qquad \text{Equation 3-4}$$

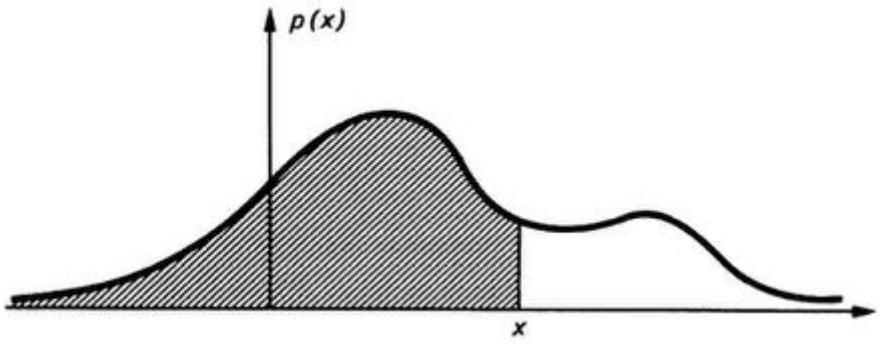

Figure 3-12 Probability density function

The first-order probability density function $p(x)$ determines the probability $p(x)dx$ that a random variable exists in the range of values x to $x + dx$. The second-order probability density function $p(x, y)$ is obtained with an additional random variable y, refer to Figure 3-13.

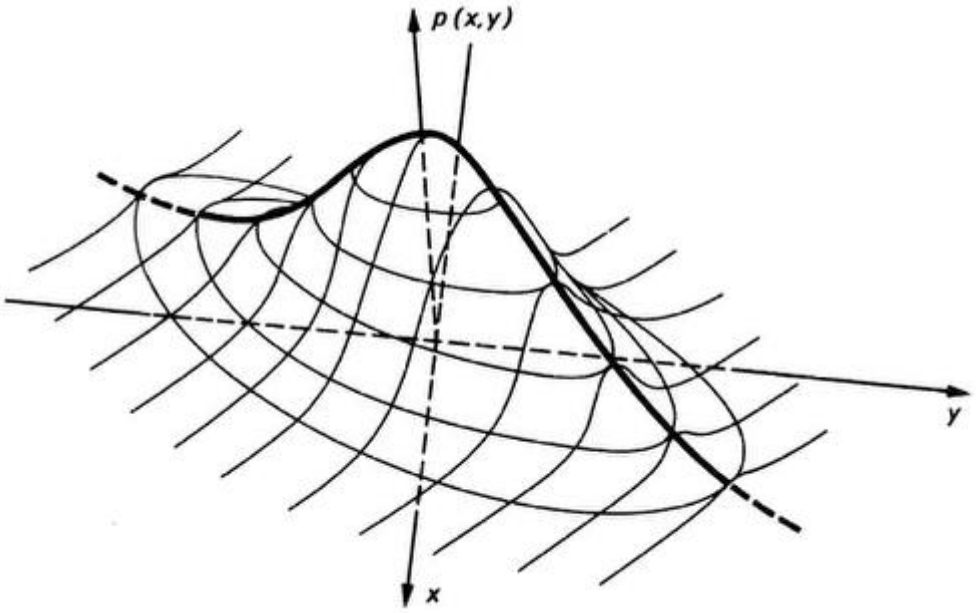

Figure 3-13 Typical second-order or joint probability density function *p*(*x*, *y*)

In stationary random process, the first order probability distributions do not depend on absolute time, but the higher order probability distributions depend on the time separation between measuring points (τ).

The autocorrelation function $R_x(\tau)$ for a random process *x(t)* is obtained as the mean value of the product $x(t) \times x(t+\tau)$. For a stationary process, $R_x(\tau)$ depends only on the separation time τ and not on the absolute time *t*, so $R_x(\tau)$ is an even function of τ as shown in Equation 3-5.

$$R_x(\tau) = E[x(t) \times x(t+\tau)] = E[x(t) \times x(t-\tau)] = R_x(-\tau) \qquad \text{Equation 3-5}$$

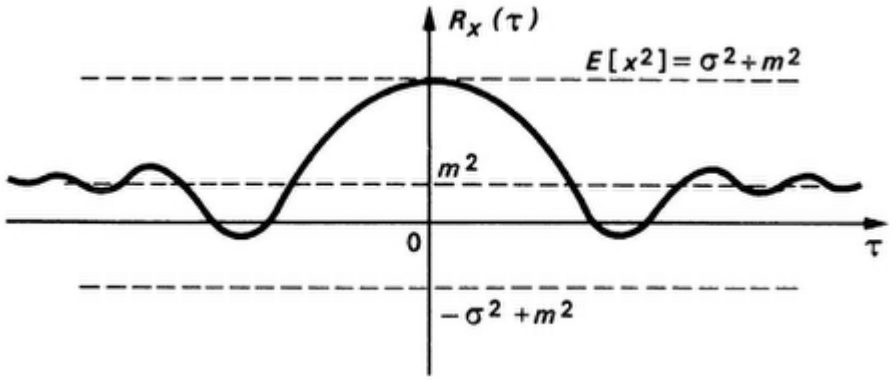

Figure 3-14 Autocorrelation function $R_x(\tau)$ of a stationary random process *x*(*t*)

The process would decay to zero in amplitude if the zero value of the random process *x*(*t*) is normalized, so the average value of the process *m*= *E*[*x*] is zero. Therefore, the Fourier transform of $R_x(\tau)$ and its inverse are respectively given by Equation 3-6 and Equation 3-7.

$$S_x(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_x(\tau) e^{-i\omega\tau} d\tau \qquad \text{Equation 3-6}$$

$$R_x(\tau) = \int_{-\infty}^{\infty} S_x(\omega) e^{i\omega\tau} d\omega \qquad \text{Equation 3-7}$$

Where $S_x(\omega)$ is the spectral density of the *x* process and is a function of angular frequency ω.

When τ= 0, the average square value of a stationary random process *x* is given by the area under a graph of spectral density $S_x(\omega)$ against ω, refer to Figure 3-15.

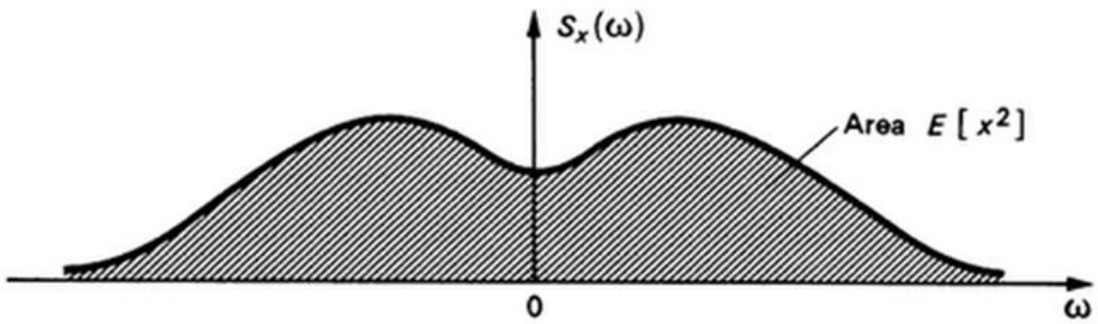

Figure 3-15 spectral density curve for zero mean stationary process when τ= 0

Here below are examples of narrow band and broad band processes.

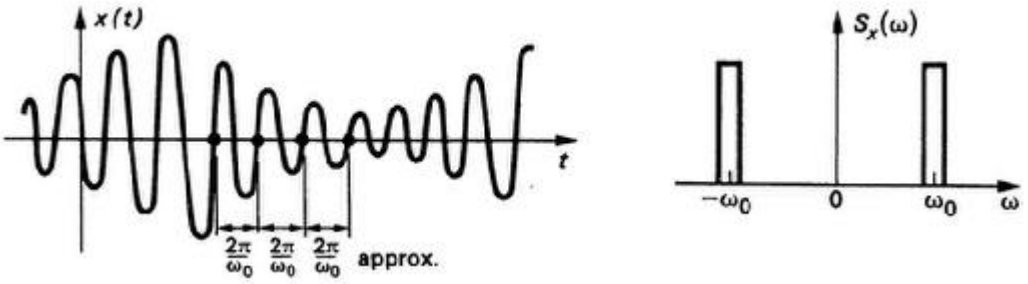

Figure 3-16 Narrow band process

Figure 3-17 broad band process

The cross correlation functions between two different stationary random functions of time $x(t)$ and $y(t)$ are obtained as the average value of the product $x(t)y(t+\tau)$, refer to Equation 3-8. Normally there is no correlation between x and y when the time separation τ is very large and maximum correlation exists when $\tau = \tau_o$, as shown in Figure 3-18. Unlike the autocorrelation function, cross-correlation function is not even in τ.

$$R_{xy}(\tau) = E[x(t)y(t+\tau)] = R_{yx}(-\tau) \qquad \text{Equation 3-8}$$

The cross spectral density of a pair of random processes is defined as the Fourier transform of the subsequent cross correlation function for the two processes in Equation 3-9.

$$S_{xy}(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_{xy}(\tau)e^{-i\omega\tau}d\tau \qquad \text{Equation 3-9}$$

And its inverse transform is given in Equation 3-10

$$R_{xy}(\tau) = \int_{-\infty}^{\infty} S_{xy}(\omega)e^{i\omega\tau}d\omega \qquad \text{Equation 3-10}$$

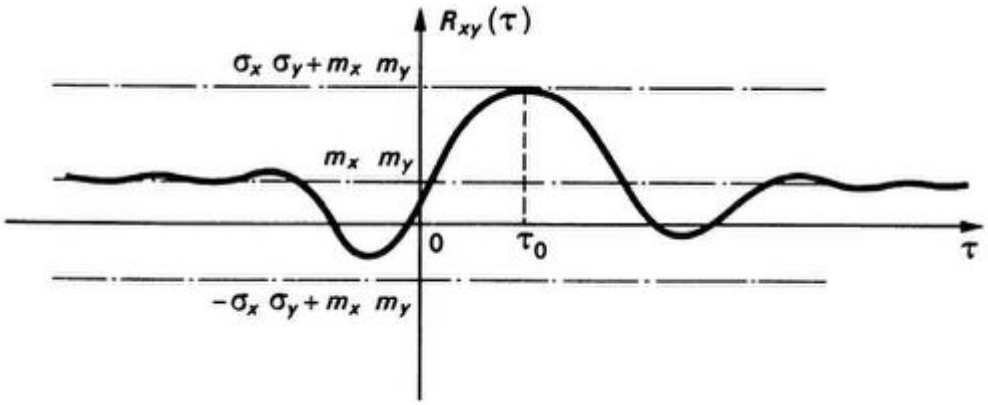

Figure 3-18 Cross-correlation function $R_{xy}(\tau)$ of stationary processes $x(t)$ and $y(t)$

Cross spectral density $S_{xy}(\omega)$ and $S_{yx}(\omega)$ are similar but the sign of their imaginary parts is reversed. Therefore, $S_{yx}(\omega)$is the complex conjugate of $S_{xy}(\omega)$, refer to Equation 3-11.

$$S_{yx}(\omega) = S^*_{xy}(\omega) \qquad \text{Equation 3-11}$$

Using the principle of superposition for linear vibrating systems (which does not change its characteristics with time), we can simplify the system so that the response to each input variable could be considered separately.

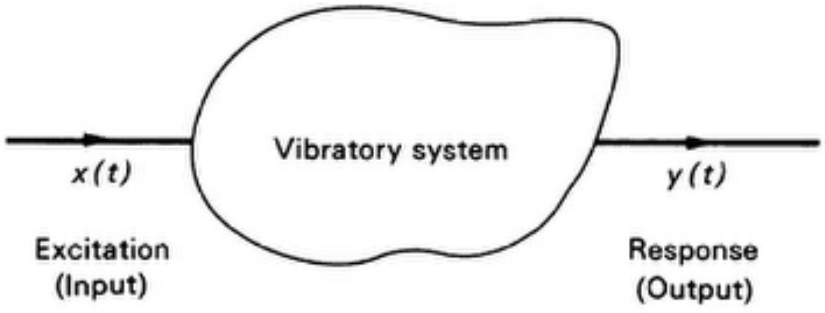

Figure 3-19 Excitation and response parameters of a linear system

If the input is a constant amplitude sine wave of fixed frequency (Equation 3-12), the steady state output will be as given in Equation 3-13.

$$x(t) = x_0 sin\omega t \qquad \text{Equation 3-12}$$

$$y(t) = y_0 sin(\omega t - \phi)$$ Equation 3-13

The transfer function (transmission characteristics) of the system is then defined by evaluating the amplitude ratio y_o/x_o and the phase angle ϕ at a series of closely spaced frequencies. If the frequency range extends from zero to infinity, then the frequency response characteristics of the system are theoretically defined as illustrated below for a linear spring-damper system.

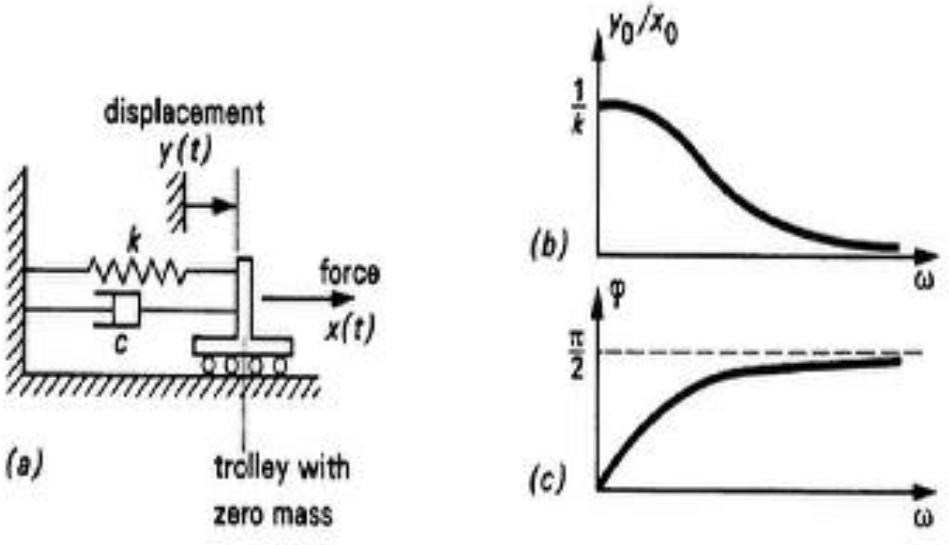

Figure 3-20 Frequency response characteristics for a simple system

The equation of motion for a linear spring of stiffness *k* and a linear viscous damper of coefficient *c*, is as follows:

$$ky + c\dot{y} = x(t)$$ Equation 3-14

Using the above equations, the amplitude ratio and phase angle are derived as respectively given in Equation 3-15 and Equation 3-16:

$$\frac{y_0}{x_0} = \frac{1}{\sqrt{(c^2\omega^2 + k^2)}}$$ Equation 3-15

$$\phi = tan^{-1}\frac{c\omega}{k}$$ Equation 3-16

It is conventional in vibration theory to represent the above quantities with a single complex number, which is called frequency response function $H(\omega)$ as shown in Equation 3-17 and Equation 3-18.

$$H(\omega) = A(\omega) - iB(\omega) \qquad \text{Equation 3-17}$$

$$|H(\omega)| = \sqrt{(A^2 + B^2)} = \frac{y_0}{x_0} ; \frac{B}{A} = \tan\phi \qquad \text{Equation 3-18}$$

The frequency response function $H(\omega)$ gives the steady state response of a system to a sine wave input. The dynamic characteristics of the system is completely define by measuring $H(\omega)$ for all frequencies. Another method of defining a system's dynamic characteristics is to measure the transient response of an initially dormant system to an impulsive input. Refer to Figure 3-21 for a typical impulse response function. The unit impulse response function for the system shown in Figure 3-20(a) is illustrated in Figure 3-22.

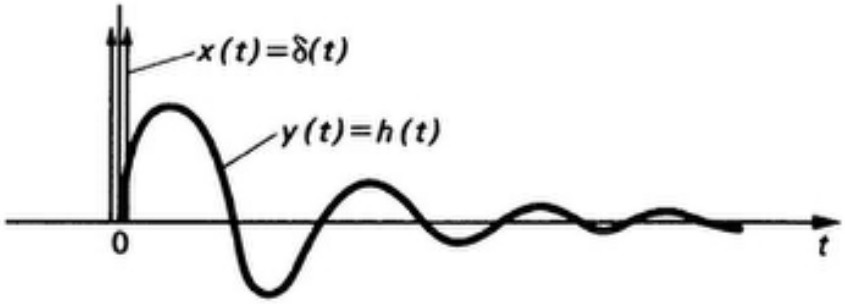

Figure 3-21 impulse response function

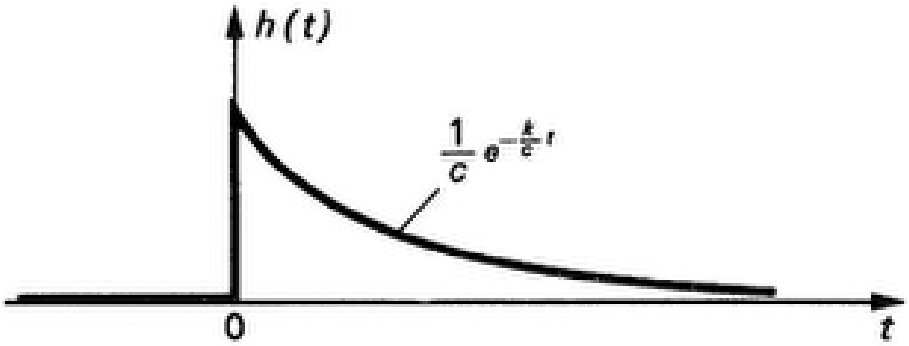

Figure 3-22 Unit impulse response function

If we take the Fourier transforms of both the impulsive input $x(t) = \delta(t)$ and the transient output $y(t) = h(t)$, we obtain a very important relationship between the Fourier transforms of the input and output, $X(\omega)$ and $Y(\omega)$, and the frequency response function $H(\omega)$, refer to Equation 3-19.

$$Y(\omega) = H(\omega)X(\omega) \qquad \text{Equation 3-19}$$

A formal solution for the output $y(t)$ is obtained in Equation 3-20, by taking the inverse transform of $Y(\omega)$, which is difficult to evaluate.

$$y(t) = \int_{-\infty}^{\infty} H(\omega) \left(\frac{1}{2\pi}\int_{-\infty}^{\infty} x(t)e^{-i\omega t}dt\right)e^{i\omega t}d\omega \qquad \text{Equation 3-20}$$

However, by breaking down an arbitrary input $x(t)$ into a series of impulses (refer to Figure 3-23), another formal solution for the response $y(t)$ is obtained in Equation 3-20. This can be achieved using the principle of superposition for a passive linear system, which decays to static equilibrium.

$$y(t) = \int_{-\infty}^{t} h(t-\tau)x(\tau)d\tau \qquad \text{Equation 3-21}$$

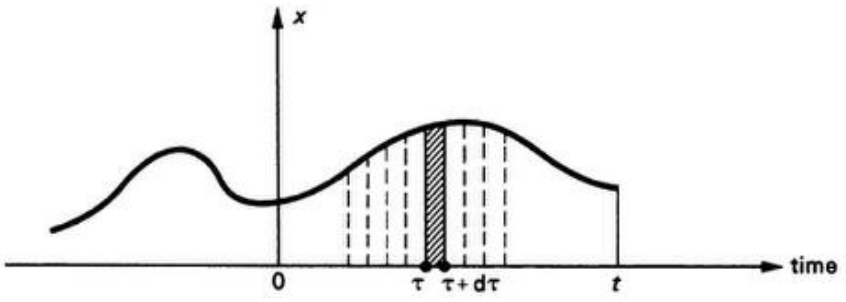

Figure 3-23 Arbitrary input *x*(*t*)

The spectral density of the output process is derived by the Fourier transform of its autocorrelation function; refer to Equation 3-22.

$$S_y(\omega) = |H(\omega)|^2 S_x(\omega) \qquad \text{Equation 3-22}$$

The mean response is obtained in Equation 3-23.

$$E[y^2] = \int_{-\infty}^{\infty} |H(\omega)|^2 S_x(\omega) d\omega \qquad \text{Equation 3-23}$$

The cross spectral density between the input and output that obtained by the Fourier transform of its cross-correlation function is given in Equation 3-24.

$$S_{xy}(\omega) = H(\omega) S_x(\omega) = S_{xy}^* = H^*(\omega) S_x(\omega) \qquad \text{Equation 3-24}$$

The output of a linear system subjected to Gaussian inputs is Gaussian and its probability distributions can be calculated if the respective mean values, variances and covariances (refer to Equation 3-3) are known. For non-Gaussian random processes, the theory becomes much more complicated. However, many naturally occurring random vibrations have the Gaussian probability distribution, refer to Figure 3-11. According to the central limit theorem, when a random process results from the summation of infinitely many random elementary events, then this process will tend to have Gaussian probability distributions. Furthermore, even when the excitation is non-Gaussian, a system's response may approximate to Gaussian if it is a narrow band response that is derived from a broad band excitation. The reason is because the convolution integral (Equation 3-20) may again be thought of as the limiting case of a linear sum of approximately independent random variables.

The characteristics of the excitation are modified by the response of the system. In most vibration problems, the system has at least one resonant frequency at which large amplitudes can be generated by small inputs. At other frequencies transmission is reduced and, at very high frequencies, the effective mass may be so high that the output is not measurable.

Since the output spectrum is confined to a narrow band of frequencies in the vicinity of the resonant frequency, the response $y(t)$ is a narrow band random process and the typical time history of $y(t)$ resembles a sine wave of varying amplitudes and phases, refer to Figure 3-24.

If the frequency response function has very sharp cut-offs above and below the resonant frequency (refer to Figure 3-25a), then its autocorrelation function is obtained from Equation 3-25.

$$R_y(\tau) = 4S_0 \frac{sin(\frac{\Delta\omega\tau}{2})}{\tau} \cos \omega_0 \tau \qquad \text{Equation 3-25}$$

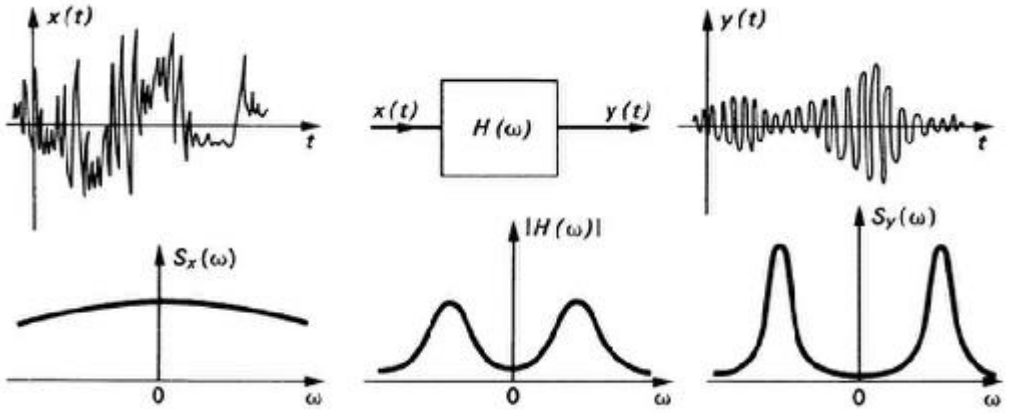

Figure 3-24 Broad band noise transmission through resonant system

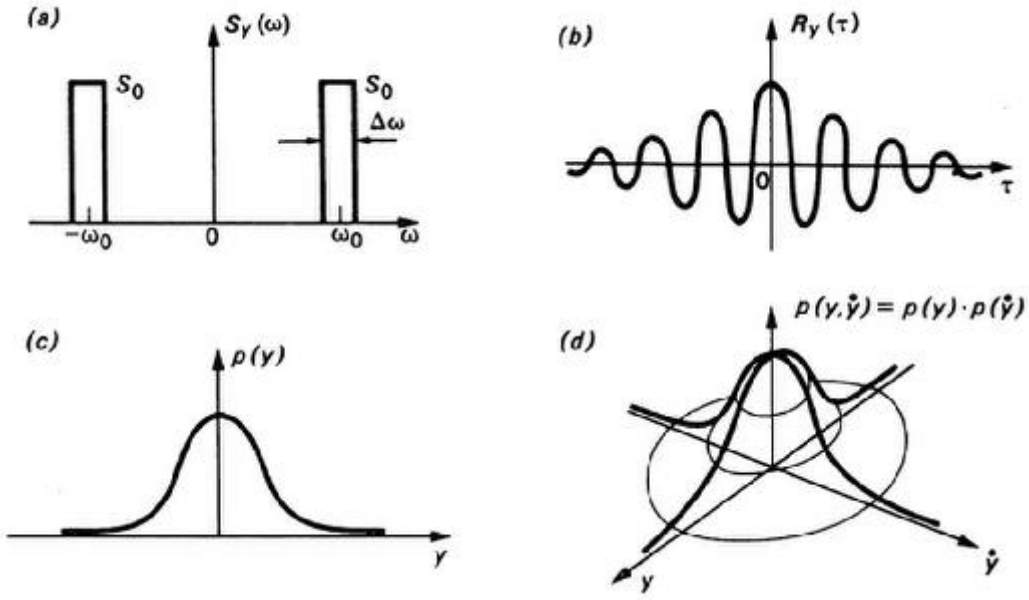

Figure 3-25 stationary, Gaussian, narrow band process

Provided that the excitation is Gaussian (refer to Figure 3-25c), then we can find the first order probability density function $p(y)$ and the second order probability density function $p(y, \dot{y})$ for the joint probability of y and its derivative $\dot{y}$ from Equation 3-26 and Equation 3-27.

$$p(y) = \frac{1}{\sqrt{2\pi}\sigma_y} e^{\frac{-y^2}{2\sigma_{\dot{y}}^2}} \qquad \text{Equation 3-26}$$

$$p(y,\dot{y}) = \frac{1}{2\pi\sigma_y\sigma_{\dot{y}}} e^{-\frac{1}{2}\left(\frac{y^2}{\sigma_y^2}+\frac{\dot{y}^2}{\sigma_{\dot{y}}^2}\right)} = p(y)p(\dot{y}) \qquad \text{Equation 3-27}$$

we need to know the frequency of crossings $y = a$ to obtain the probability distribution of peaks, refer to Figure 3-26.

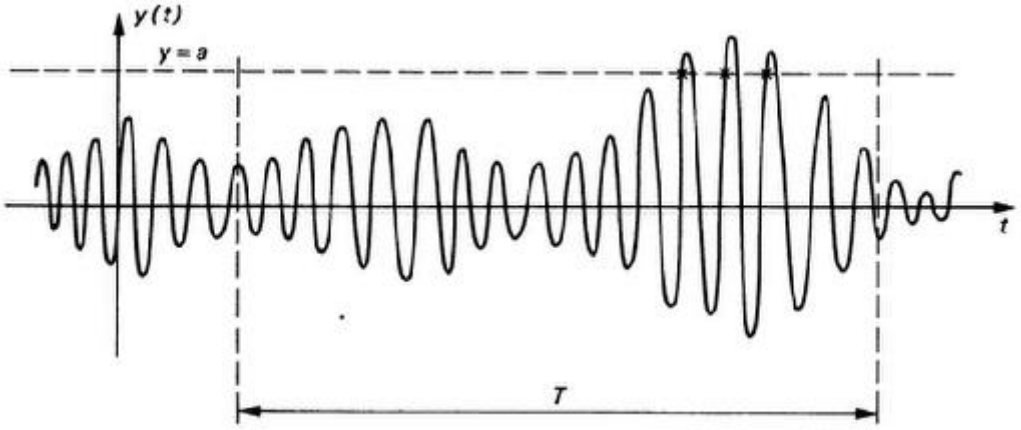

Figure 3-26 Narrow band process

For a stationary process, the average number of crossings is proportional to the time interval T, refer to Equation 3-28.

$$N_a^+(T) = v_a^+ T \qquad \text{Equation 3-28}$$

Where v_{a^+} is the average frequency of crossing $y = a$.

y=0 is the average frequency for the process.

There will be a positive slope crossing of $y = a$ in the next time interval dt if, at time t,

$$y < a \text{ and } \frac{dy}{dt} > \frac{a-y}{dt}$$

In other words, if the values of y and $\dot{y}$ lie within this shaded wedge (refer to Figure 3-27 b), then there will be a positive slope crossing of $y = a$ in time dt. The probability that they do lie in the shaded wedge can be obtained from the joint probability density function $p(y, \dot{y})$ and is just the shaded volume shown in Figure 3-27 a; i.e., the volume under the probability surface above the shaded wedge of acceptable values of y and $\dot{y}$ as given below.

$$\text{Prob}\left(\begin{matrix}\text{positive slope crossing}\\ \text{of } y=a \text{ in time } dt\end{matrix}\right) = \iint p(y,\dot{y})dyd\dot{y} \qquad \text{Equation 3-29}$$

Furthermore, the frequency parameter in terms of the joint probability density function is derived from Equation 3-30.

$$\nu_a^+ = \int_0^\infty p(a,\dot{y})\dot{y}d\dot{y} \qquad \text{Equation 3-30}$$

For a Gaussian process:

$$\nu_a^+ = \frac{\sigma_{\dot{y}}}{2\pi\sigma_y} e^{-a^2/2\sigma_y^2} \qquad \text{Equation 3-31}$$

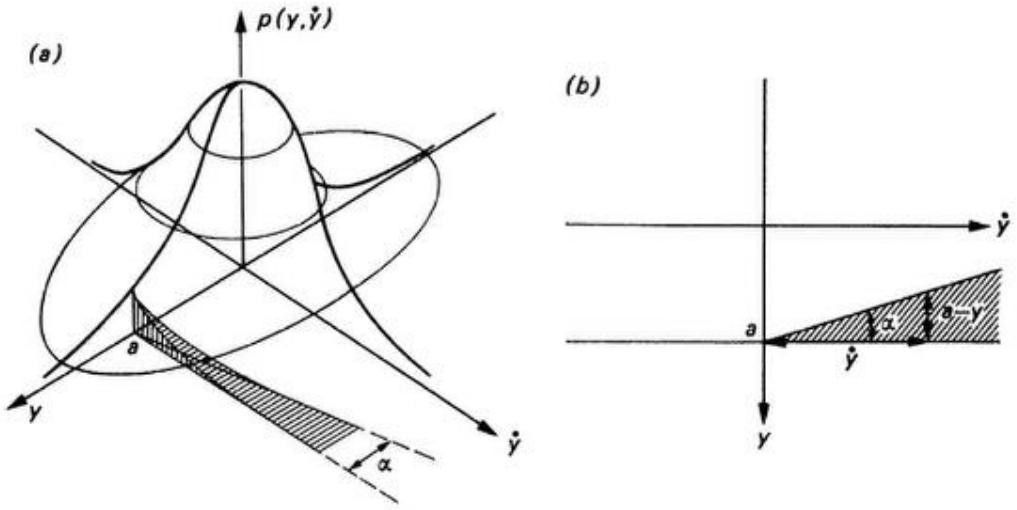

Figure 3-27 Probability of crossing *y= a*

The probability that the magnitude of a peak, chosen at random, lies in the range a to $a + da$, is $p_p(a)da$ (refer to Figure 3-28).

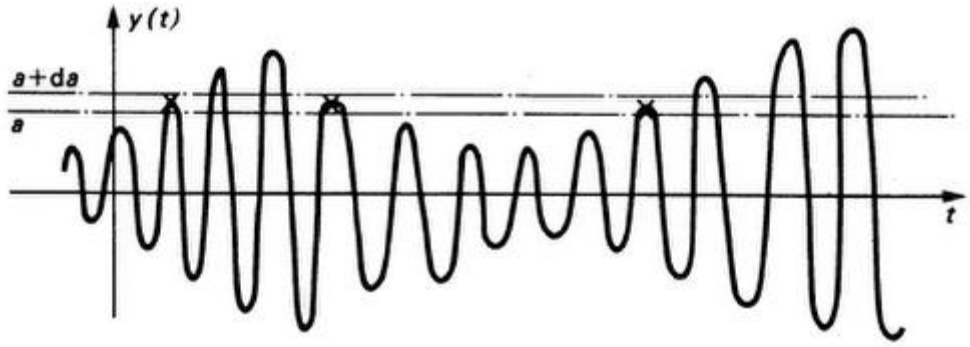

Figure 3-28 Identification of peaks in the band y = a to y = a + da

The probability that any peak is greater than a is

$$\int_a^\infty p_p(a)da = \frac{\nu_a^+}{\nu_0^+} \qquad \text{Equation 3-32}$$

Therefore, the probability density function for the occurrence of peaks is derived in Equation 3-33, provided that this is a smooth narrow band process with each cycle crossing the mean level $y= 0$, so all the maxima occur above $y= 0$ and all the minima occur below $y= 0$.

$$-p_p(a) = \frac{1}{\nu_0^+}\frac{d}{da}(\nu_a^+) \qquad \text{Equation 3-33}$$

If $y(t)$ is Gaussian, then the probability density of peaks will have a Rayleigh distribution as given in Equation 3-34 and shown in Figure 3-29.

$$p_p(a) = \frac{a}{\sigma_y^2} e^{-a^2/2\sigma_y^2} \quad 0 \le a \le \infty \qquad \text{Equation 3-34}$$

The function $p_p(a)$ has its maximum value at $a= \sigma_y$, which is the standard deviation of the y process. It is clear from Figure 3-29 that the majority of peaks are about this magnitude. The probability that any peak, chosen at random, exceeds a is,

$$\text{Prob}(\text{peak value exceeds } a) = e^{-a^2/2\sigma_y^2} \qquad \text{Equation 3-35}$$

Our analysis of peaks that leads to the Rayleigh distribution for a Gaussian process is based on the assumption that the narrow band process $y(t)$ resembles a sine wave of varying amplitude and phase.

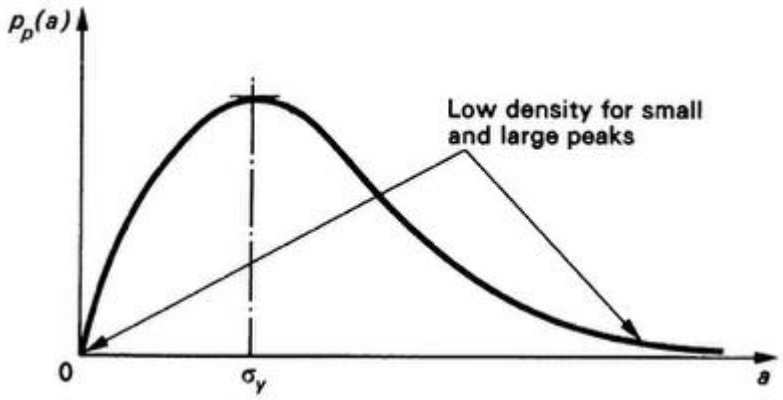

Figure 3-29 Rayleigh distribution of peaks for a Gaussian narrow band process

The existence of high frequency components in a more general narrow-band spectrum that is shown in Figure 3-30(a) introduces additional maxima in a narrow band process, which is illustrated in Figure 3-30(b). However, the Rayleigh distribution of peaks assumes only one maximum for each zero crossing, which means that irregularities in the smooth form of the sine wave approximation are not accepted.

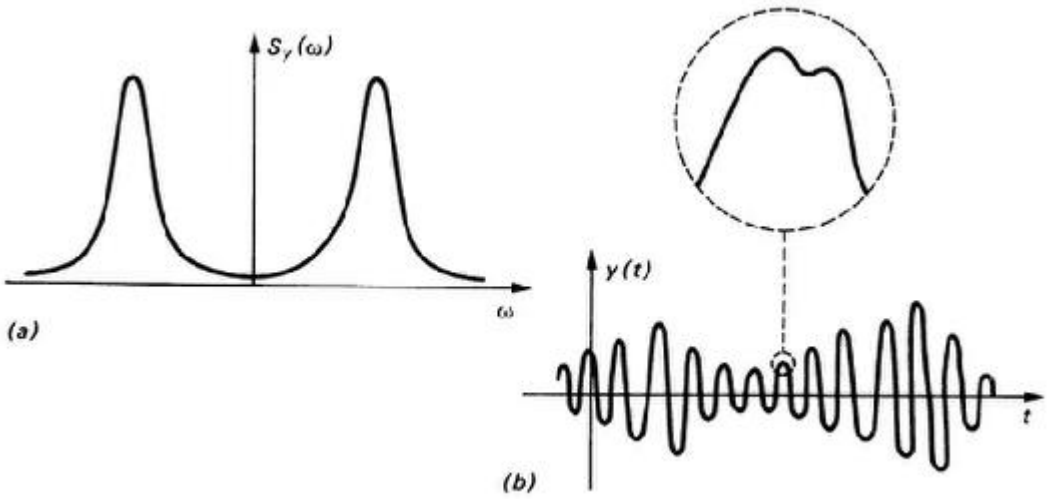

Figure 3-30 irregularities in a narrow band process

The above discussion was to clarify the basic mathematical theory of random process. The practical aspect of the subject involves experimental measurements with emphasis on measuring the spectral density of a random process or the cross-spectral density between two random processes. The spectral measurement is of prime importance since it simplifies the input-output relations for spectral density of a linear system subjected to random excitation.

The schematic of a spectrum analyser is shown in Figure 3-31. The input signal $x(t)$, which is a sample function of an ergodic (and therefore stationary) random process, is filtered to a narrow-band filter. The filter centre frequency is based on the predominant frequencies present in a vibration signal. The filter theoretical frequency response is shown in Figure 3-31(b). The average output of the spectrum analyser is proportional to the spectral density of the input process at the filter centre frequency. The mean output level is therefore a direct measure of the input spectral density.

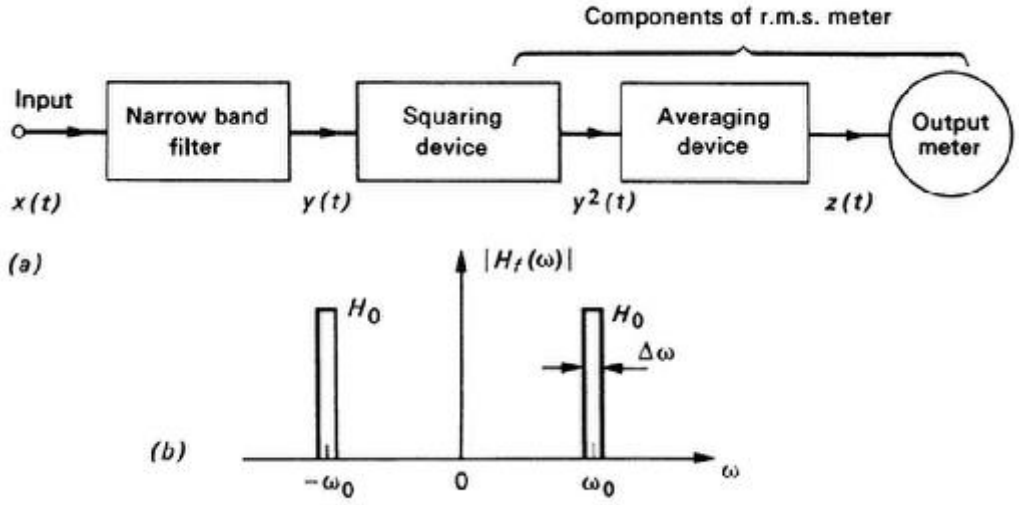

Figure 3-31 Spectrum Analyser

Selective filters are employed to transform time domain to frequency domain, which automatically reduce the effective bandwidth and therefore reduce the statistical reliability of the results that are obtained.

Until the late 1960s, Fourier transforms of correlation functions were employed to estimate spectra from measured data. By the advent of the fast Fourier transform (FFT), a computer algorithm for calculating discrete Fourier transforms (DFTs), spectral estimates are obtained directly from the original time series, which is quicker and more accurate. Furthermore, the most important development in signal analysis has been the wavelet transform. Unlike Fourier transforms that use sines and cosines as the basis functions for decomposing general signals, alternative families of orthogonal basis functions (wavelets) are employed in wavelet transforms.

Wavelet analysis provides an alternative way of breaking a signal down into its constituent parts overcoming the disadvantages of Fourier analysis where frequency information can only be extracted for the complete duration of a signal.

3.3 The applicability of the spectral method

The methodology used here is a frequency domain analysis using spectral density functions and the transfer function approach to model the response spectrum. The global structural analysis is carried out in the frequency domain with stochastic linearization for nonlinear forces and damping. Direct frequency response analysis for modal analysis is applied to determine the transfer functions. For simplicity, the model for short crested sea has been left out.

Ocean waves are the source of the fatigue inducing stress range acting on the structural system being analysed. The wave and current induced loads for a jacket type platform are likely to be drag dominated. This could be due to typical sizes of the submerged structural elements. Thus, methods based on linearized hydrodynamic loads should be used in a structural analysis. The spectral analysis method employed should reflect dynamic response characteristics of the structure in the fatigue assessment with due consideration of dynamic amplification.

Spectral based fatigue analysis technique is complex and numerically difficult to achieve. Since frequency domain formulation is based on probabilistic methods it will require the linearization of loads and structural response, so the superposition of stress range transfer functions from unit amplitude waves are considered valid.

The method is most applicable when there is a linear relationship between the wave height and the wave induced loads and the structural response to these loads is linear. This will require the existence of short periods during which wave statistics of the random sea may be assumed not to change (steady sea-states).

The main advantage of the spectral method in frequency domain analysis is that the computations are relatively efficient compared to time domain analysis methods (DNV, 2010). Other advantages are the successful use of wave power spectra to describe water surface elevation, the ease of handling nonlinear effects and the resulting solution being physically interpretable (Etube, 1999).

Determination of the frequency response function is the main task of spectral fatigue analysis. The frequency response function defines the relationship between the stresses at a specified structural location per unit wave height. For irregular waves, the sea-state is represented by a wave spectrum. The frequency domain method is well suited for systems exposed to random

wave environments, since the random response spectrum $S_R(\omega)$ can be directly computed from the transfer function $R(\omega)$ and the wave spectrum $S_\eta(\omega)$ using the Equation 3-36.

$$S_R(\omega) = S_\eta(\omega) R^2(\omega) \qquad \text{Equation 3-36}$$

Where ω is angular frequency

Short term response statistics in each sea-state is determined with the assumption that the short term stress variation in a given sea-state is a random narrow banded stationary process. This will be the prerequisite to represent the short-term distribution of stress range by a Rayleigh distribution. Furthermore, the long-term response distribution can be obtained by accumulating the short term response statistics for all sea-states in the scatter diagram.

A spectral based fatigue assessment produce results in terms of fatigue induced damage or fatigue life using Miner's summation hypothesis, which is referred to as a direct method. This hypothesis applies for a narrow band process in which separate stress cycles can be identified, and suggests that if n_i cycles of stress occur at a level of stress at which N_i constant stress cycles would cause fracture, then the fractional damage done by the n_i cycles is n_i/N_i. Failure is to be expected when the sum of all the fractional damages is equal to one; i.e., $\Sigma(n_i/N_i)=1$.

Fatigue damage is mostly associated with low or moderate seas; hence, confused short-crested sea conditions must be allowed. Confused short-crested seas result in a kinetic energy spread, which is modelled using the cosine-squared approach, $(2/\pi)\cos^2\theta$. Generally, cosine-squared spreading is assumed from +90 to –90 degrees on either side of the selected wave heading. Applying the wave spreading function modifies the spectral moment (ABS, 2010). However, for simplicity, the model for short crested sea has is ignored (Skjong, 1991). Although wave directionality and energy spreading generally reduce the structural response, their long term statistics are not yet commonly available (Kawamoto, 1982).

3.4 Uncertainty in the process

There is uncertainty involved in the evaluation of the response and its statistics. Wave forces and subsequent stresses involve certain nonlinear effects. The main source of uncertainty is the nonlinearity due to the drag term. Some potential errors when using a frequency domain analysis could be due to higher frequency harmonics in the wave force, underestimating wave forces in the wave crest when using linear kinematics up to the mean water level or nonlinear wave response on drag dominant structure.

The transfer function is no longer linear if it is dependent on the height of the regular wave that is selected. The evaluation of statistical extreme is more complex since the process is not Gaussian. In this regard, special care is required for wave height selection when generating the transfer function because the application of a spectral method requires a linear process to yield reasonable results with subsequent response calculations in view of the nonlinear nature of the drag forces (HSE, 2000).

In this context, linear means proportional to wave amplitude. It is assumed that the wave force on the structure is monotonic and that the responses are linear with wave height. Although this may not be the case, by suitable linearization it is still possible to use the powerful technique of spectral analysis with non-monotonic and nonlinear systems.

Fatigue in offshore structures is a typical high-cycle phenomenon, which is caused by many cycles with small stress ranges. A few extreme storms with return periods above one year are considered to be insignificant in fatigue damage. Consequently, the response of a structure in sea states with low wave heights and short wave periods (from the wave height of 0.3 m to the wave height corresponding to one year return period) is the response of interest in fatigue environment which linearization yields a good result.

3.5 Wave selection for transfer function

Wave selection should be considered based on the characteristics of the structure as well as the environment, so the transfer functions are adequately defined over the relevant frequency range. This range should include frequencies of sea-states with significant energy in the wave scatter diagram. High frequency cut-off should be considered for dynamic analysis.

An appropriate level of non-linear (drag) wave loading is introduced by proper selection of wave heights used for the transfer functions. Constant wave steepness is commonly used to provide a simple relationship between the wave height and frequency. The steepness is the ratio of wave height to wave length in the range of 1:15 to 1:25, which can be obtained by a suitable calibration process. The wave length is related to the frequency by the appropriate wave theory.

To accurately define the dynamic response peak, the natural frequency and three closely spaced frequencies on each side of the natural frequency should be included. Good definition of peaks and valleys of the transfer function can be verified on the base shear transfer function plot. The features of the frequency grid selection are shown in Figure 3-32 (repeat of Figure 1-2).

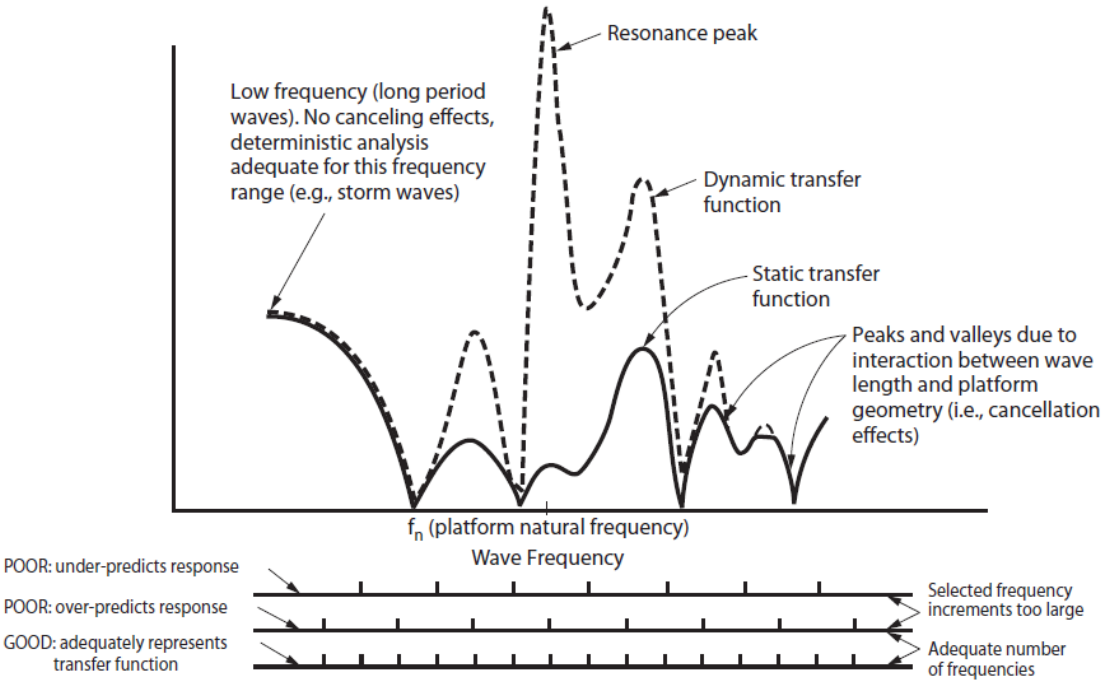

Figure 3-32 Frequency grid selection

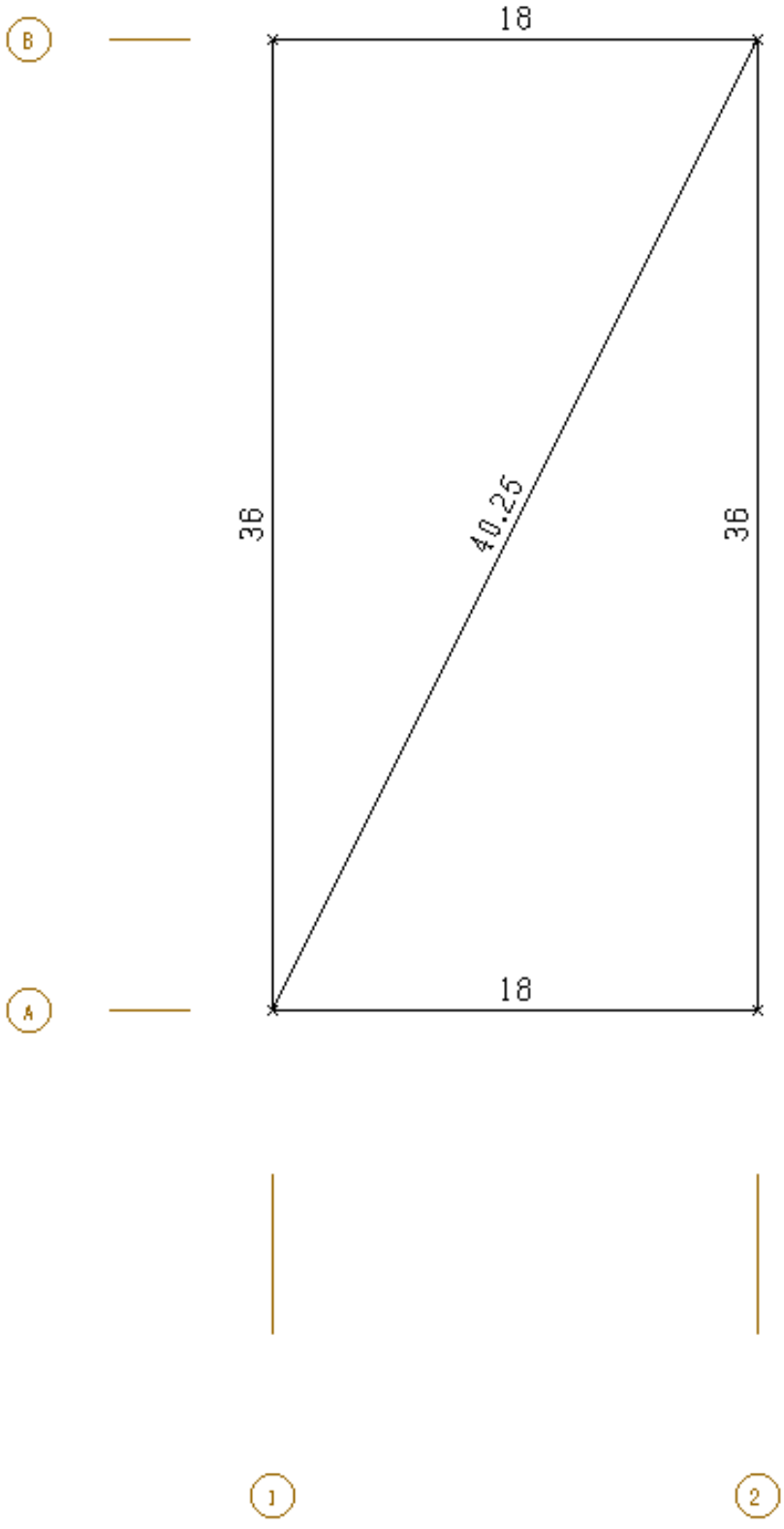

Figure 3-33 Leg spacing at Jacket work point (m)

Table 3-2 First three modes of the structure

Mode	Period (seconds)
1	3.372
2	1.901
3	1.374

Table 3-3 Along Row A and B (*d* =18 m)

n	Enhancement wave		Cancellation wave	
	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)
1	3.397	0.294	4.804	0.208
2	2.402	0.416	2.774	0.360
3	1.961	0.510	2.148	0.466

Table 3-4 Along Row 1 and 2 (*d* = 36m)

n	Enhancement wave		Cancellation wave	
	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)
1	4.804	0.208	6.794	0.147
2	3.397	0.294	3.922	0.255
3	2.774	0.360	3.038	0.329

Table 3-5 Along diagonal (*d* = 40.25)

n	Enhancement wave		Cancellation wave	
	Period (sec)	Frequency (Hz)	Period (sec)	Frequency (Hz)
1	5.079	0.197	7.183	0.139
2	3.592	0.278	4.147	0.241
3	2.933	0.341	3.213	0.311

Wave cancelation and enhancement effects can be incorporated by selecting the wave frequencies in the vicinity of the troughs and peaks in the applied wave load transfer functions. These frequencies correspond to specific wave lengths as multiples or fractions of leg spacing.

Enhancement and cancelation wave periods (T_e and T_c) correspond to wave lengths that are specific multiples or a fraction of key dimensions such as the main leg spacing, and are respectively given by Equation 3-37 and Equation 3-38.

$$T_e = \sqrt{d/1.56n} \qquad \text{Equation 3-37}$$

$$T_c = \sqrt{d/1.56(n-0.5)} \qquad \text{Equation 3-38}$$

d= leg spacing at jacket work point (m) as shown in Figure 3-33; *n* = 1, 2, 3

Sufficient intermediate frequencies and selection of frequencies corresponding to peaks of the wave spectra included in the scatter diagram are required for accurate definition of wave input energy. The initial frequency grid is enhanced to include the first three modes of the structure (Table 3-2), enhancement/cancelation wave period (Table 3-3 to Table 3-5) and additional wave steps around the first period of the platform as given in Table 3-6. A comparison between initial and final frequency grid is presented in Figure 3-34 to Figure 3-37.

Table 3-6 Enhanced Frequency Grid

10 steps	From 10.00 seconds to 5.00 seconds at an interval of 0.50 seconds
4 steps	From 5.00 seconds to 4.00 seconds at an interval of 0.25 seconds
20 steps	From 4.00 seconds to 3.00 seconds at an interval of 0.05 seconds
21 steps	From 2.5 seconds to 1.00 seconds at an interval of 0.10 seconds

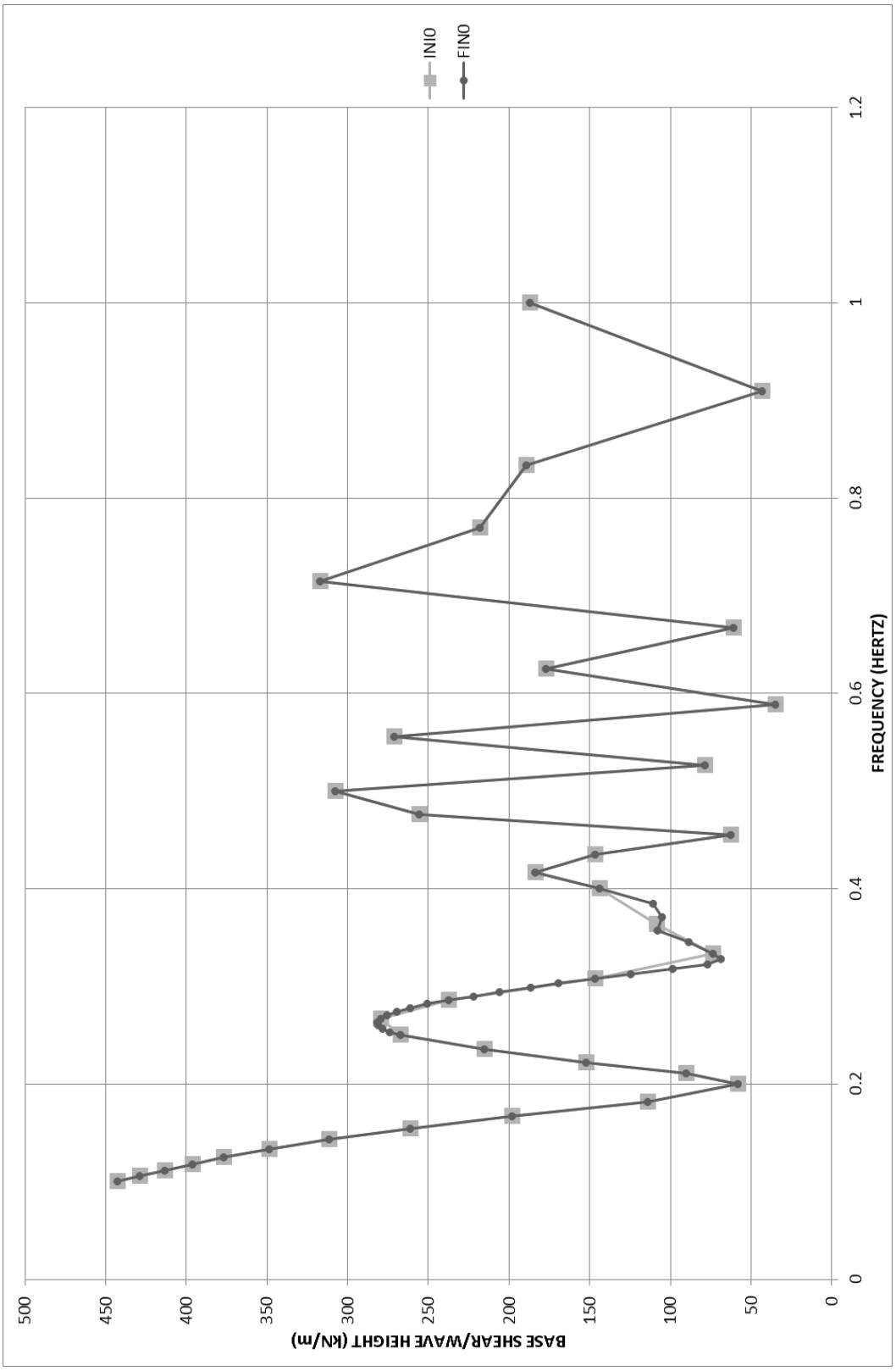

Figure 3-34 Initial and Final frequency grid comparison at 0°

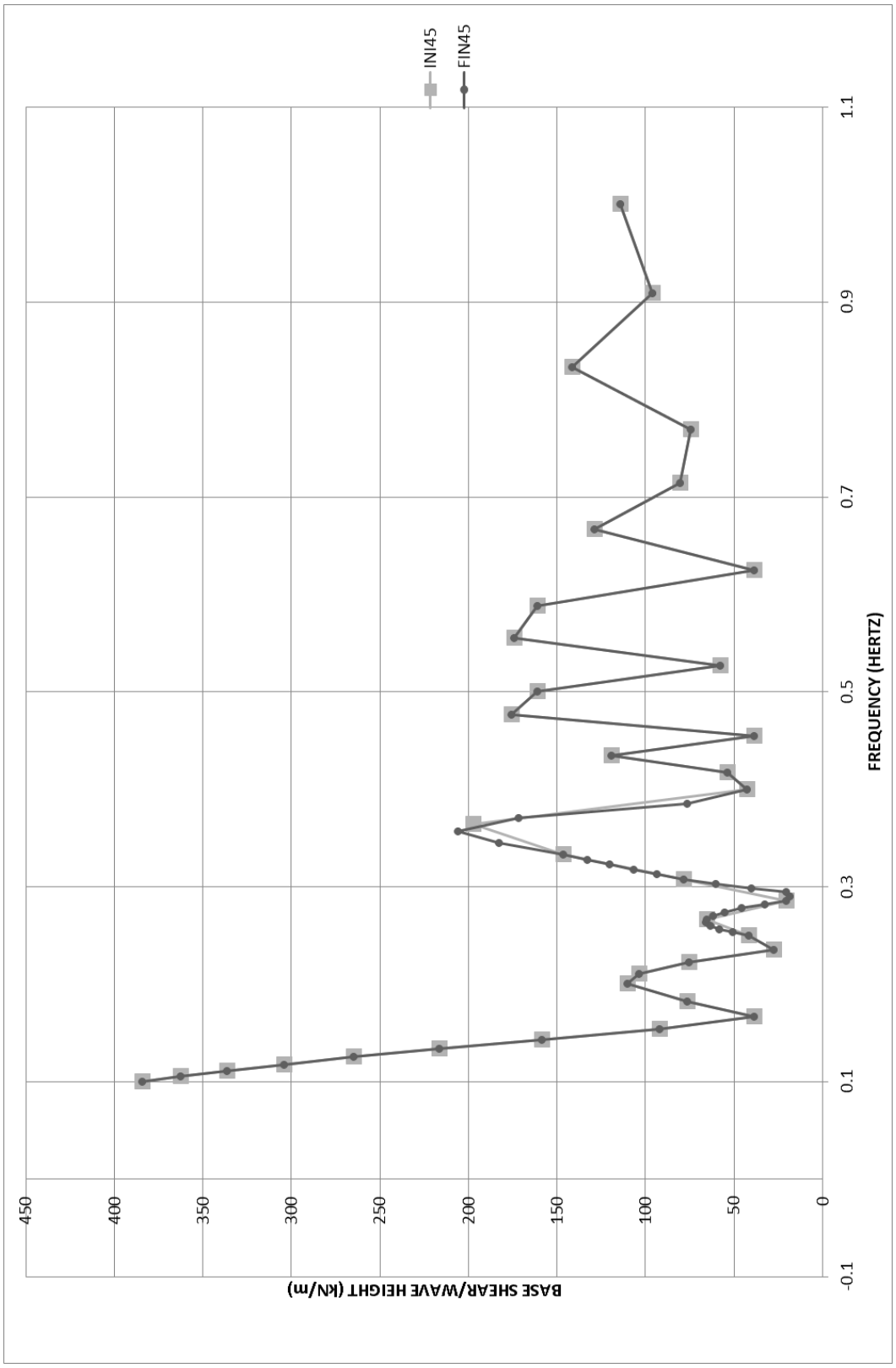

Figure 3-35 Initial and Final frequency grid comparison at 45°

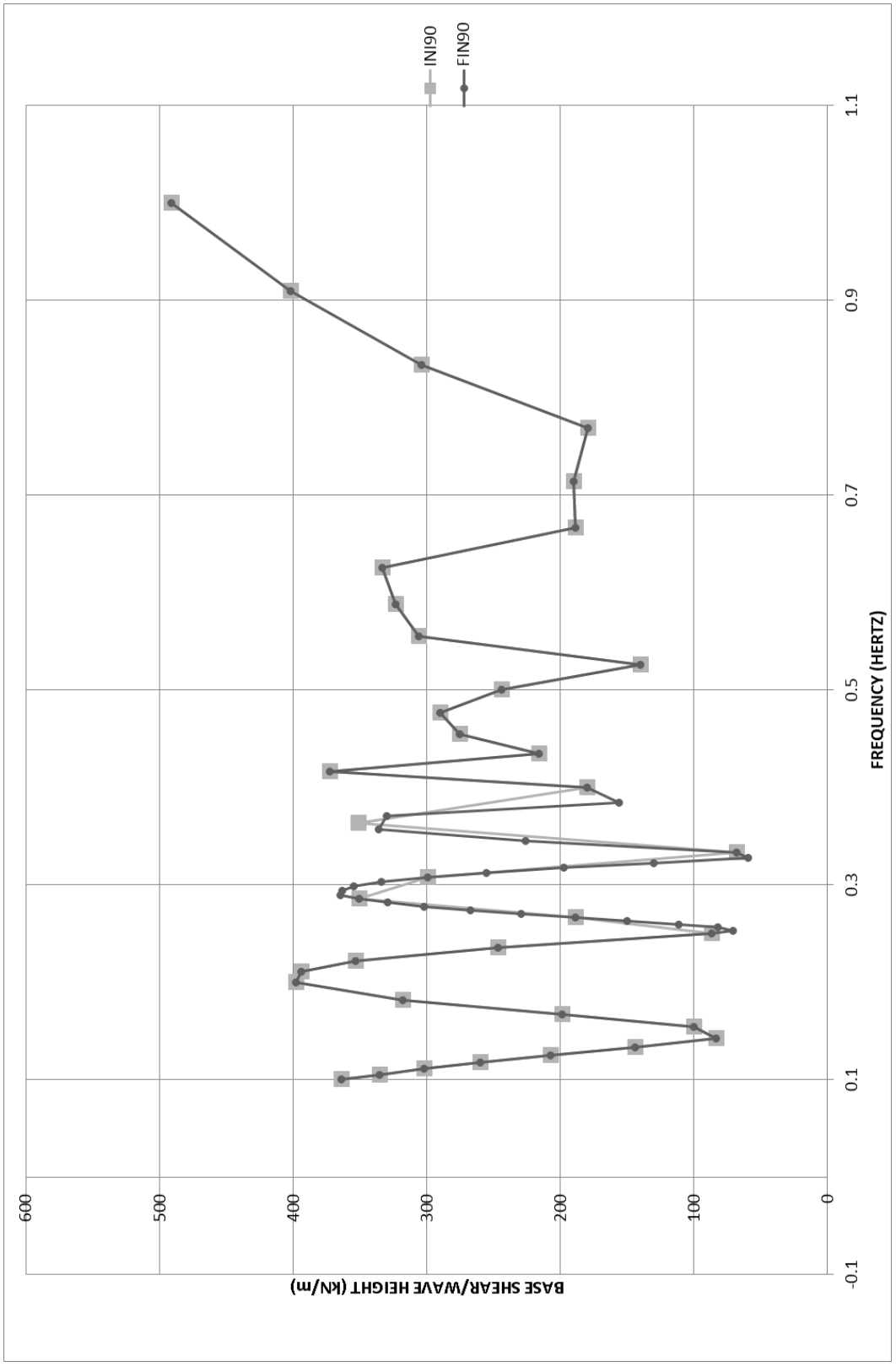

Figure 3-36 Initial and Final frequency grid comparison at 90°

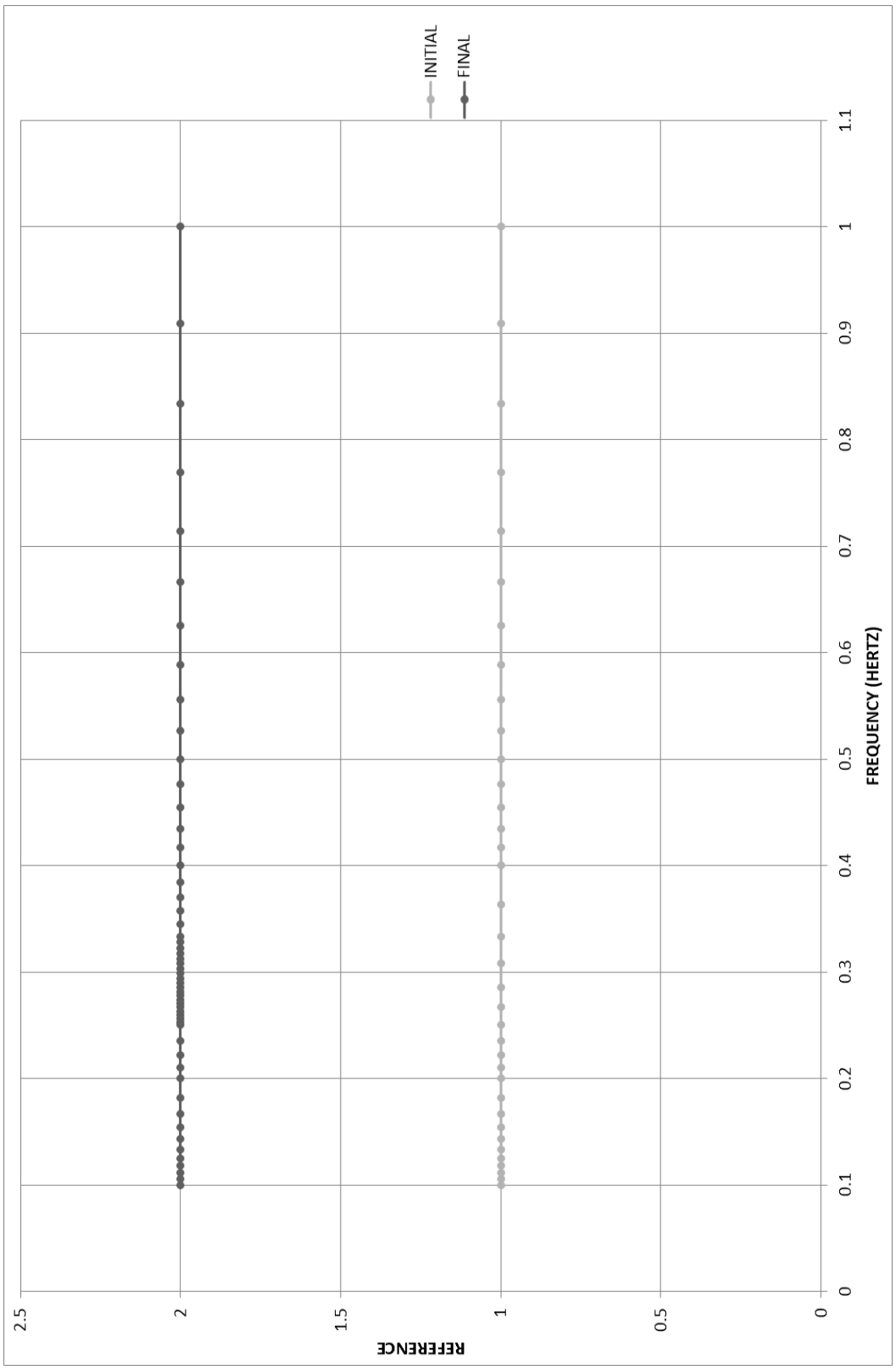

Figure 3-37 Frequency grid distribution

3.6 Calibration Method

The calibration is based on matching of global response parameters. For matching purposes, the base shear wave load is commonly used. The sea-state that contributes most to fatigue damage is considered. For this purpose, the centre of fatigue damage scatter diagrams along each direction are considered, as shown in Table 3-7 to Table 3-9.

Table 3-7 Directional wave scatter diagram (0 degree)

4.25								1		
3.75								1		
3.25							1	1		
2.75							5	1		
2.25						6	34			
1.75					1	165	39	1		
1.25				1	246	394	1			
0.75				705	1141	54				
0.25		1	100	1262	167					
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-8 Directional wave scatter diagram (45 degree)

4.25										
3.75										
3.25										
2.75										
2.25						2	4			
1.75						8	3			
1.25				3	25	35				
0.75			2	157	170	5				
0.25		1	83	574	47					
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-9 Directional wave scatter diagram (90 degree)

4.25										
3.75										
3.25										
2.75										
2.25										
1.75							1			
1.25					1	1				
0.75				22	20	2				
0.25			27	201	29					
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Dynamic Transfer functions are developed for the average wave steepness related to the weighted centre of damage in the scatter diagram and presented in Figure 3-48 to Figure 3-55. The weighing factor is the mean value of the normalized static base shear transfer function over the width of each cell in the scatter diagram as presented in Table 3-20 to Table 3-27. This weighing factor introduces a stress period dependency, which allows the cancellation effects to be reflected in the fatigue damage scatter diagram.

Fatigue damage is obtained from Equation 3-39 and presented in Table 3-28 to Table 3-30.

$$D_{ij} = N_{ij} \frac{(0.5(H_i + H_{i+1}))^m}{0.5(T_j + T_{j+1})} \quad \text{Equation 3-39}$$

Where; m = slope of S-N curve = 3

The weighted fatigue damage is calculated using Equation 3-40 and presented in Table 3-31 to Table 3-33.

$$D_{ij} = N_{ij} * \frac{(W_j * 0.5 * (H_i + H_{i+1}))^m}{0.5 * (T_j + T_{j+1})} \quad \text{Equation 3-40}$$

Where D_{ij} is the weighted fatigue damage in each cell of the fatigue scatter diagram and W_j is the average period dependant weighing factor that is presented in Table 3-10.

Table 3-10 Average Weighing factors (W_j)

T_p / Dir.	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5
0°	0.0	0.409	0.378	0.466	0.369	0.289	0.599	0.800	0.912	0.977
45°	0.0	0.306	0.314	0.191	0.195	0.209	0.261	0.568	0.797	0.945
90°	0.0	0.571	0.509	0.402	0.598	0.616	0.261	0.290	0.502	0.648

From fatigue damage calculations, the wave height (H_c) and wave period (T_c) at corresponding centre of fatigue damage scatter diagram is calculated by Equation 3-41.

$$\begin{cases} H_c = \frac{\sum D_{ij} H_{si}}{\sum D_{ij}} \\ T_c = \frac{\sum D_{ij} T_{pi}}{\sum D_{ij}} \end{cases}$$ Equation 3-41

From these values, the most probable maximum wave in the sea-state at the centre of the damage scatter diagram is determined from Equation 3-42 and presented in Table 3-11.

$$\begin{cases} H_{ref} = 1.86 H_c \\ T_{ref} = T_c \end{cases}$$ Equation 3-42

Table 3-11 Fatigue centroid

	Fatigue Centroid					Weighted Fatigue Centroid				
	H_c	T_c	H_{ref}	T_{ref}	H_{ref}/L_{ref}	H_c	T_c	H_{ref}	T_{ref}	H_{ref}/L_{ref}
0°	1.46	5.19	2.72	5.19	1/15.5	2.02	5.82	3.75	5.82	1/14.1
45°	1.19	4.72	2.22	4.72	1/16	1.32	4.95	2.45	4.95	1/15.6
90°	0.84	4.27	1.55	4.27	1/18	0.81	4.36	1.50	4.36	1/19.7

This wave period is compared with the static base shear transfer function (Figure 3-39 to Figure 3-47) for the direction of interest to confirm that it does not fall in the valley of the transfer function. If it falls in the valley, then it is shifted to the adjacent peak depending on wave energy distribution as presented in Table 3-12.

Table 3-12 Shifted fatigue centroid

	H_{ref}	T_{ref}	H_c	T_c
0°	1.371	3.75	0.737	3.75
45°	2.438	5.00	1.311	5
90°	2.438	5.00	1.311	5

To account for the sensitivity of the structure, typically a broadside, an end-on and a diagonal direction are considered for calibration and a single representative steepness is chosen from these. In this case, an average design wave steepness of 1/16 is used. The wave height to be

used for each wave frequency in the fatigue analysis is calculated from Equation 3-43 using metric units.

$$\begin{cases} L_{ref} = 1.56{T_{ref}}^2 \\ \text{wave steepness} = {H_{ref}}/{L_{ref}} \end{cases} \quad \text{Equation 3-43}$$

Use of the constant wave steepness will give unrealistically large wave heights at small wave frequencies. Therefore, a maximum height equal to the wave height with a one year return period and ending with a period corresponding to a wave height of 0.3 m should normally be used (API, 2007).

Root mean square (RMS) base shear wave loads are calculated for the sea-state at the centre of the fatigue damage scatter diagram, using standard spectral analysis techniques. For this, *SACS* (Offshore Structural Design and Analysis Software) modules are used by making the mass equal to zero (to eliminate inertial loads) and fully damping the structure (to make a low forcing frequency). Hence, the response calculated will be the static response of interest. This will provide an RMS base shear value for each wave steepness and direction as given in Table 3-13 and highlighted in SACS results as follows. Values of H_c and T_c are used to determine the static RMS (kN) values for the response function plots (refer to Figure 3-56 to Figure 3-64) along the three wave directions.

Table 3-13 RMS base shear (kN)

Wave Direction	Wave Steepness		
	1:25	1:20	1:15
0°	24.97	24.83	24.59
45°	22.01	21.68	21.06
90°	80.86	80.47	79.67

Steepness 1:25

****** OVERTURNING MOMENT AND BASE SHEAR RMS VALUES ******

(SINGLE AMPLITUDE)

SPECTRUM NO.	TYPE	SIG. WAVE HEIGHT M	DOMINANT PERIOD SECS	WAVE DIRECTION DEGREES	** TRANSFER FUNCTION ** FIRST WAVE	LAST WAVE	ALL CONVERGED	**** DYNAMIC RMS **** MOMENT KN-M	SHEAR KN
1	JS	0.74	3.75	0.000	1	36	YES	776.	24.97
2	JS	1.31	5.00	45.000	37	72	YES	614.	22.01
3	JS	1.31	5.00	90.000	73	108	YES	2504.	80.86

Steepness 1:20

****** OVERTURNING MOMENT AND BASE SHEAR RMS VALUES ******

(SINGLE AMPLITUDE)

SPECTRUM NO.	TYPE	SIG. WAVE HEIGHT M	DOMINANT PERIOD SECS	WAVE DIRECTION DEGREES	** TRANSFER FUNCTION ** FIRST WAVE	LAST WAVE	ALL CONVERGED	**** DYNAMIC RMS **** MOMENT KN-M	SHEAR KN
1	JS	0.74	3.75	0.000	1	36	YES	771.	24.83
2	JS	1.31	5.00	45.000	37	72	YES	603.	21.68
3	JS	1.31	5.00	90.000	73	108	YES	2490.	80.47

Steepness 1:15

****** OVERTURNING MOMENT AND BASE SHEAR RMS VALUES ******

(SINGLE AMPLITUDE)

SPECTRUM NO.	TYPE	SIG. WAVE HEIGHT M	DOMINANT PERIOD SECS	WAVE DIRECTION DEGREES	** TRANSFER FUNCTION ** FIRST WAVE	LAST WAVE	ALL CONVERGED	**** DYNAMIC RMS **** MOMENT KN-M	SHEAR KN
1	JS	0.74	3.75	0.000	1	36	YES	763.	24.59
2	JS	1.31	5.00	45.000	37	72	YES	588.	21.06
3	JS	1.31	5.00	90.000	73	108	YES	2473.	79.67

A stationary process is one whose statistics do not change with time. For every RMS stress there exists an average time, T_z, between zero crossings with a positive slope for a stationary Gaussian process with zero mean. This period is called the *Zero Crossing Period* . For a narrow band process, this is the average period or the reciprocal of the average frequency of the process. Assuming zero mean and a Rayleigh distribution of peaks, the most probable maximum [MPM] base shear wave load is found by using Equation 3-44 (HSE, 2000) and presented in Table 3-14.

$$\frac{MPM}{RMS} = \left[2 \ln \frac{T}{T_Z}\right]^{0.5} \qquad \text{Equation 3-44}$$

Where T is the 3 hours' duration of the storm in seconds (3 × 60 × 60 = 10,800 seconds) and T_z is the mean zero crossing period of the wave in the sea-state at the centre of damage scatter diagram. This will provide the maximum base shear wave load from the spectral calculation for each wave steepness and direction. The corresponding base shear wave load range is double the MPM base shear wave load.

Wave power spectra can be generally classified into two characteristic forms. These are related to either the fetch-limited, developing sea conditions without swell, or the fully developed seas, and can be reasonably described by the JONSWAP and the Pierson-Moskowitz spectra, respectively. The shape of the stress (strain) power spectra is important because corrosion crack growth of the structural steels in tubular joints is sensitive to the frequency content. Therefore, it is necessary to simulate the correct frequency content, and hence power spectra, of typical wave loading (Kam, 1990). For sea-states described by a JONSWAP spectrum, T_z is assumed to be equal to T_p /1.28.

Table 3-14 MPM VALUES

Wave Direction	Wave Steepness		
	1:25	1:20	1:15
0^0	97.213	96.860	95.879
45^0	94.174	92.411	89.110
90^0	355.756	354.044	351.858

Spectral Base Shear Range is given as 2MPM for each wave direction and wave steepness in Table 3-15.

Table 3-15 Spectral base shear

Wave Direction	Wave Steepness		
	1:25	1:20	1:15
0°	194.426	193.720	191.758
45°	188.348	184.822	178.220
90°	711.512	708.088	703.716

Deterministic base shear is presented in Table 3-16 from values highlighted in SACS' results.

Table 3-16 Deterministic base shear range

0°	136.366 + 136.260 = 272.626kN
45°	96.234 + 96.224 = 192.458kN
90°	348.209 + 348.113 = 696.322kN

Deterministic base shear from SACS' results (refer to Table 3-16)

**** WAVE DESCRIPTION FOR LOAD CASE SW1 ****

WAVE THEORY ********** CLASSICAL AIRY
WAVE HEIGHT ********** 1.371 M
WATER DEPTH ********** 42.720 M
WAVE PERIOD ********** 3.750 SECS
WAVE LENGTH ********** 21.948 M
ANGLE FROM X TOWARD Y ** 0.000 DEGREES
MUDLINE ELEVATION ****** -41.600 M
WAVE CELERITY ********** 5.853 M /SEC
MAX. NO. SEG/MEMBER **** 10
MIN. NO. SEG/MEMBER **** 1
CREST POSITION DETERMINED BY MAXIMUM SHEAR
STARTING CREST POSITION 0.000 M
NO. STEPS ********** 36
STEP SIZE ********** 0.610 M
CREST WATER DEPTH ****** 42.72 M
TROUGH WATER DEPTH ***** 42.72 M

********** SEASTATE LOADS FOR WAVE PASSING THROUGH STRUCTURE **********

1.4 M. WAVE AT 0.0 DEG

LOAD CONDITION	CREST POSITION M	DEG	LOAD	MUDLINE ELEVATION
MAXIMUM MOMENT ABOUT MUDLINE	18.29	300.00	5085.233 KN-M	-41.60 M
MAXIMUM SHEAR AT MUDLINE	17.68	290.00	136.366 KN	-41.60 M
MINIMUM MOMENT ABOUT MUDLINE	7.32	120.00	-4981.785 KN-M	-41.60 M
MINIMUM SHEAR AT MUDLINE	6.71	110.00	-136.260 KN	-41.60 M
MAXIMUM FORCE UPWARD	1.83	30.00	33.716 KN	-41.60 M
MAXIMUM FORCE DOWNWARD	12.80	210.00	-21.916 KN	-41.60 M

**** WAVE DESCRIPTION FOR LOAD CASE SW2 ****

WAVE THEORY ********** CLASSICAL AIRY
WAVE HEIGHT ********** 2.438 M
WATER DEPTH ********** 42.720 M
WAVE PERIOD ********** 5.000 SECS
WAVE LENGTH ********** 39.018 M
ANGLE FROM X TOWARD Y ** 45.000 DEGREES
MUDLINE ELEVATION ****** -41.600 M
WAVE CELERITY ********** 7.804 M /SEC
MAX. NO. SEG/MEMBER **** 10
MIN. NO. SEG/MEMBER **** 1
CREST POSITION DETERMINED BY MAXIMUM SHEAR
STARTING CREST POSITION 0.000 M
NO. STEPS ********** 36
STEP SIZE ********** 1.084 M
CREST WATER DEPTH ****** 42.72 M
TROUGH WATER DEPTH ***** 42.72 M

********** SEASTATE LOADS FOR WAVE PASSING THROUGH STRUCTURE **********

2.4 M. WAVE AT 45.0 DEG

LOAD CONDITION	CREST POSITION M	CREST POSITION DEG	LOAD	MUDLINE ELEVATION
MAXIMUM MOMENT ABOUT MUDLINE	32.52	300.00	3648.682 KN-M	-41.60 M
MAXIMUM SHEAR AT MUDLINE	10.84	100.00	96.234 KN	-41.60 M
MINIMUM MOMENT ABOUT MUDLINE	13.01	120.00	-3379.133 KN-M	-41.60 M
MINIMUM SHEAR AT MUDLINE	30.35	280.00	-96.224 KN	-41.60 M
MAXIMUM FORCE UPWARD	6.50	60.00	53.177 KN	-41.60 M
MAXIMUM FORCE DOWNWARD	26.01	240.00	-29.795 KN	-41.60 M

**** WAVE DESCRIPTION FOR LOAD CASE SW3 ****

WAVE THEORY ********** CLASSICAL AIRY
WAVE HEIGHT ********** 2.438 M
WATER DEPTH ********** 42.720 M
WAVE PERIOD ********** 5.000 SECS
WAVE LENGTH ********** 39.018 M
ANGLE FROM X TOWARD Y ** 90.000 DEGREES
MUDLINE ELEVATION ****** -41.600 M
WAVE CELERITY ********** 7.804 M /SEC
MAX. NO. SEG/MEMBER **** 10
MIN. NO. SEG/MEMBER **** 1
CREST POSITION DETERMINED BY MAXIMUM SHEAR
STARTING CREST POSITION 0.000 M
NO. STEPS ********** 36
STEP SIZE ********** 1.084 M
CREST WATER DEPTH ****** 42.72 M
TROUGH WATER DEPTH ***** 42.72 M

********** SEASTATE LOADS FOR WAVE PASSING THROUGH STRUCTURE **********

2.4 M. WAVE AT 90.0 DEG

LOAD CONDITION	CREST POSITION M	CREST POSITION DEG	LOAD	MUDLINE ELEVATION
MAXIMUM MOMENT ABOUT MUDLINE	30.35	280.00	13019.681 KN-M	-41.60 M
MAXIMUM SHEAR AT MUDLINE	10.84	100.00	348.209 KN	-41.60 M
MINIMUM MOMENT ABOUT MUDLINE	10.84	100.00	-12801.345 KN-M	-41.60 M
MINIMUM SHEAR AT MUDLINE	30.35	280.00	-348.113 KN	-41.60 M
MAXIMUM FORCE UPWARD	3.25	30.00	95.008 KN	-41.60 M
MAXIMUM FORCE DOWNWARD	22.76	210.00	-72.506 KN	-41.60 M

The spectral base shear is compared against the deterministic base shear. In order to linearize the wave effects, the drag and inertia coefficients are enhanced by the ratio of deterministic base shear to spectral base shear, refer to the Table 3-17 and Table 3-18.

Table 3-17 Enhanced drag coefficient

Cd	Smooth members (initial = 0.6)			Rough members (initial = 0.7)		
Wave	Wave Steepness			Wave Steepness		
Direction	1:25	1:20	1:15	1:25	1:20	1:15
00	0.808	0.813	0.821	0.943	0.948	0.957
450	0.659	0.669	0.689	0.769	0.780	0.803
900	0.649	0.652	0.659	0.757	0.761	0.768
Cd	0.821			0.957		

Table 3-18 Enhanced mass coefficient

Cm	Smooth members (initial = 2.0)			Rough members (initial = 2.0)		
Wave	Wave Steepness			Wave Steepness		
Direction	1:25	1:20	1:15	1:25	1:20	1:15
0^0	2.694	2.709	2.736	2.694	2.709	2.736
45^0	2.196	2.230	2.295	2.196	2.230	2.295
90^0	2.163	2.174	2.195	2.163	2.174	2.195
Cm	2.736			2.736		

Fatigue demand and fatigue strength are established, then compared to one another to assess the adequacy of the structural component with respect to fatigue using a damage accumulation rule and a fatigue safety check. This approach is denoted as the *Miner Rule*. Calculated fatigue life is the computed life, in units of time (or number of cycles) for a particular structural detail considering its appropriate S-N curve (ABS, 2010). It can be clearly seen that fatigue life is overestimated (about four times) when the calibration process is not undertaken, refer to Figure 3-38.

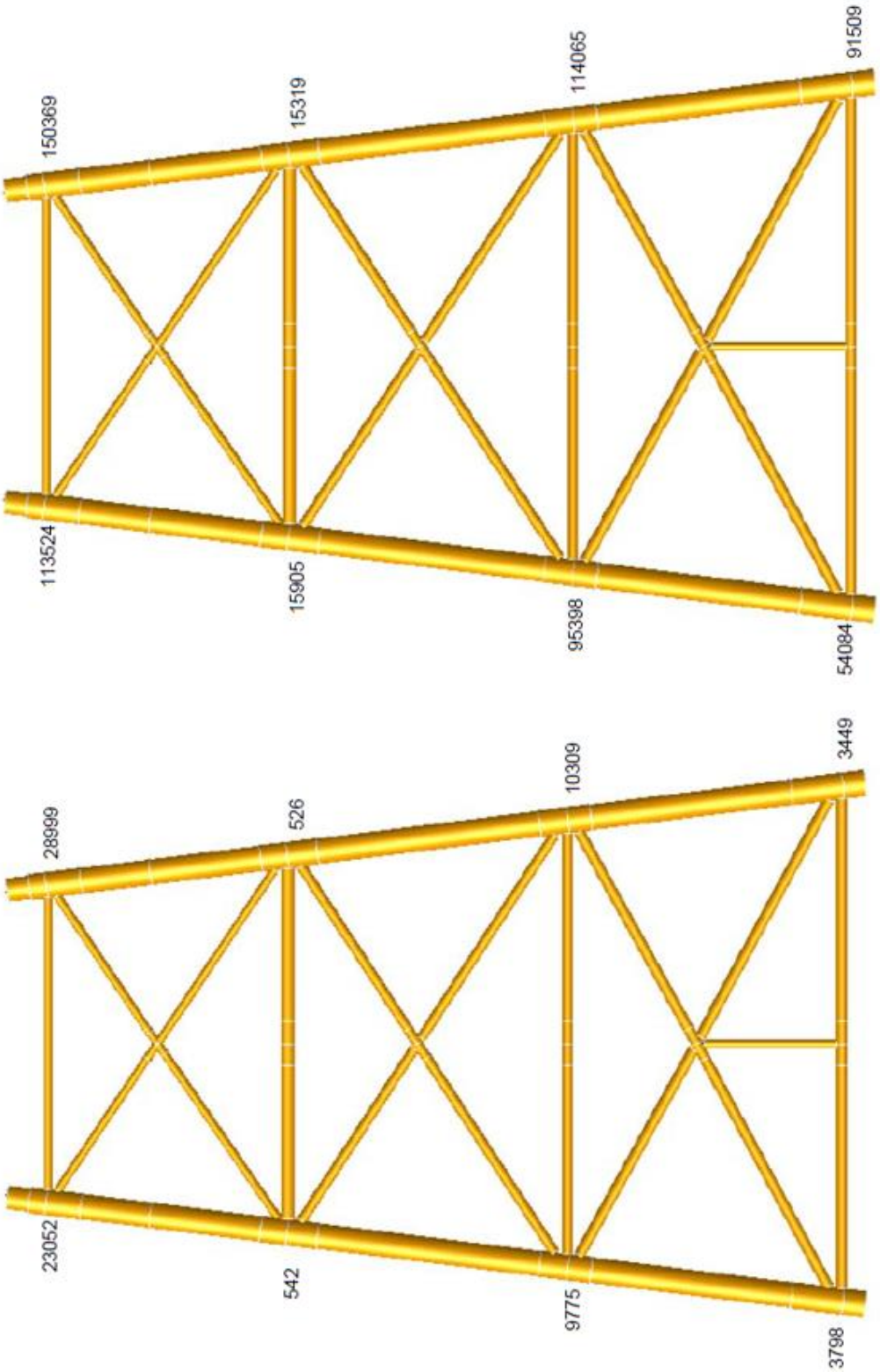

Figure 3-38 Fatigue life comparison (years)

Table 3-19 Weighing factor (steepness 1/25, 0°)

0°	Steepness 1/25		Transfer function	Weighing factor
T	BS	Hs		
10.00	1747.209	5.920	295.14	
9.50	1581.797	5.424	291.63	0.986
9.00	1409.108	4.929	285.88	
8.50	1230.404	4.440	277.12	0.935
8.00	1048.718	3.960	264.83	
7.50	864.948	3.497	247.34	0.830
7.00	681.423	3.054	223.12	
6.50	499.823	2.636	189.61	0.628
6.00	321.940	2.247	143.28	
5.50	160.981	1.888	85.27	0.305
5.00	64.216	1.561	41.14	
4.75	93.086	1.409	66.07	
4.50	139.385	1.264	110.27	0.384
4.25	176.039	1.128	156.06	
4.00	192.362	0.999	192.55	
3.75	176.983	0.878	201.58	
3.50	130.647	0.765	170.78	0.489
3.25	66.350	0.659	100.68	
3.00	31.508	0.562	56.06	
2.75	37.796	0.472	80.08	
2.50	37.506	0.390	96.17	0.397
2.40	49.342	0.360	137.06	
2.30	36.594	0.330	110.89	
2.20	14.538	0.302	48.14	
2.10	50.760	0.275	184.58	
2.00	55.934	0.250	223.74	
1.90	14.438	0.225	64.17	
1.80	40.108	0.202	198.55	
1.70	4.942	0.180	27.46	
1.60	19.710	0.160	123.19	
1.50	6.544	0.140	46.74	0.429
1.40	28.754	0.122	235.69	
1.30	16.449	0.106	155.18	
1.20	12.434	0.090	138.16	
1.10	2.976	0.076	39.16	
1.00	8.780	0.062	141.61	

Table 3-20 Weighing factor (steepness 1/20, 0°)

0°	Steepness 1/20		Transfer function	Weighing factor
T	BS	Hs		
10.00	2241.665	7.400	302.93	
9.50	2012.340	6.780	296.81	0.979
9.00	1787.684	6.161	290.16	
8.50	1555.761	5.550	280.32	0.921
8.00	1320.969	4.950	266.86	
7.50	1085.162	4.371	248.26	0.812
7.00	850.753	3.817	222.89	
6.50	620.104	3.295	188.20	0.609
6.00	400.992	2.809	142.75	
5.50	196.796	2.361	83.35	0.295
5.00	81.378	1.951	41.71	
4.75	116.599	1.761	66.21	
4.50	174.848	1.580	110.66	0.374
4.25	220.120	1.410	156.11	
4.00	240.281	1.249	192.38	
3.75	219.504	1.097	200.09	
3.50	161.042	0.956	168.45	0.474
3.25	84.794	0.824	102.91	
3.00	37.912	0.702	54.01	
2.75	46.848	0.590	79.40	
2.50	46.716	0.488	95.73	0.383
2.40	59.544	0.449	132.61	
2.30	45.522	0.413	110.22	
2.20	18.124	0.378	47.95	
2.10	63.186	0.344	183.68	
2.00	69.882	0.312	223.98	
1.90	18.096	0.282	64.17	
1.80	50.076	0.253	197.93	
1.70	6.190	0.226	27.39	
1.60	24.162	0.200	120.81	
1.50	8.376	0.176	47.59	0.414
1.40	36.056	0.153	235.66	
1.30	20.612	0.132	156.15	
1.20	14.976	0.112	133.71	
1.10	3.268	0.094	34.77	
1.00	10.758	0.078	137.92	

Table 3-21 Weighing factor (steepness 1/15, 0°)

0°	Steepness 1/15		Transfer function	Weighing factor
T	BS	Hs		
10.00	3232.664	9.916	326.00	
9.50	2862.820	9.085	315.12	0.965
9.00	2500.432	8.256	302.86	
8.50	2142.750	7.437	288.12	0.881
8.00	1798.028	6.634	271.03	
7.50	1458.453	5.857	249.01	0.758
7.00	1132.472	5.115	221.40	
6.50	821.943	4.416	186.13	0.559
6.00	525.248	3.764	139.55	
5.50	245.842	3.163	77.72	0.268
5.00	116.404	2.614	44.53	
4.75	157.766	2.359	66.88	
4.50	235.090	2.117	111.05	0.350
4.25	294.299	1.889	155.80	
4.00	321.564	1.673	192.21	
3.75	290.794	1.471	197.68	
3.50	210.616	1.281	164.42	0.435
3.25	109.878	1.104	99.53	
3.00	52.190	0.941	55.46	
2.75	62.670	0.791	79.23	
2.50	62.520	0.654	95.60	0.354
2.40	78.922	0.602	131.10	
2.30	59.652	0.553	107.87	
2.20	24.742	0.506	48.90	
2.10	83.754	0.461	181.68	
2.00	93.174	0.418	222.90	
1.90	22.906	0.377	60.76	
1.80	66.144	0.339	195.12	
1.70	10.302	0.302	34.11	
1.60	32.344	0.268	120.69	
1.50	11.228	0.235	47.78	0.385
1.40	47.706	0.205	232.71	
1.30	28.632	0.177	161.76	
1.20	19.722	0.151	130.61	
1.10	4.216	0.127	33.20	
1.00	14.732	0.105	140.30	

Table 3-22 Weighing factor (steepness 1/25, 45°)

45°	Steepness 1/25		Transfer function	Weighing factor
T	BS	Hs		
10.00	1498.190	5.920	253.07	
9.50	1313.401	5.424	242.15	0.953
9.00	1124.608	4.929	228.16	
8.50	929.708	4.440	209.39	0.820
8.00	732.146	3.960	184.89	
7.50	536.146	3.497	153.32	0.597
7.00	352.333	3.054	115.37	
6.50	183.740	2.636	69.70	0.286
6.00	72.023	2.247	32.05	
5.50	109.297	1.888	57.89	0.226
5.00	127.918	1.561	81.95	
4.75	108.584	1.409	77.06	
4.50	70.059	1.264	55.43	0.210
4.25	21.537	1.128	19.09	
4.00	31.711	0.999	31.74	
3.75	43.683	0.878	49.75	
3.50	10.439	0.765	13.65	0.204
3.25	38.896	0.659	59.02	
3.00	58.136	0.562	103.44	
2.75	66.330	0.472	140.53	
2.50	13.480	0.390	34.56	0.333
2.40	13.952	0.360	38.76	
2.30	29.836	0.330	90.41	
2.20	8.232	0.302	27.26	
2.10	34.630	0.275	125.93	
2.00	28.320	0.250	113.28	
1.90	10.220	0.225	45.42	
1.80	25.436	0.202	125.92	
1.70	22.812	0.180	126.73	
1.60	4.668	0.160	29.18	
1.50	13.063	0.140	93.31	0.329
1.40	7.548	0.122	61.87	
1.30	6.418	0.106	60.55	
1.20	9.208	0.090	102.31	
1.10	5.490	0.076	72.24	
1.00	5.302	0.062	85.52	

Table 3-23 Weighing factor (steepness 1/20, 45°)

45°	Steepness 1/20		Transfer function	Weighing factor
T	BS	Hs		
10.00	1948.595	7.400	263.32	
9.50	1694.509	6.780	249.93	0.945
9.00	1434.859	6.161	232.89	
8.50	1175.751	5.550	211.85	0.798
8.00	917.609	4.950	185.38	
7.50	667.967	4.371	152.82	0.572
7.00	432.499	3.817	113.31	
6.50	219.804	3.295	66.71	0.266
6.00	83.687	2.809	29.79	
5.50	135.167	2.361	57.25	0.212
5.00	157.506	1.951	80.73	
4.75	132.576	1.761	75.28	
4.50	84.840	1.580	53.70	0.197
4.25	25.488	1.410	18.08	
4.00	39.688	1.249	31.78	
3.75	53.497	1.097	48.77	
3.50	12.311	0.956	12.88	0.192
3.25	48.802	0.824	59.23	
3.00	70.742	0.702	100.77	
2.75	83.622	0.590	141.73	
2.50	16.120	0.488	33.03	0.316
2.40	17.618	0.449	39.24	
2.30	35.602	0.413	86.20	
2.20	10.340	0.378	27.35	
2.10	43.142	0.344	125.41	
2.00	35.072	0.312	112.41	
1.90	12.590	0.282	44.65	
1.80	31.168	0.253	123.19	
1.70	27.398	0.226	121.23	
1.60	6.156	0.200	30.78	
1.50	16.310	0.176	92.67	0.307
1.40	9.066	0.153	59.25	
1.30	6.740	0.132	51.06	
1.20	11.725	0.112	104.69	
1.10	6.486	0.094	69.00	
1.00	6.334	0.078	81.21	

Table 3-24 Weighing factor (steepness 1/15, 45°)

45°	Steepness 1/15		Transfer function	Weighing factor
T	BS	Hs		
10.00	2784.367	9.916	280.80	
9.50	2398.803	9.085	264.04	0.936
9.00	2010.136	8.256	243.48	
8.50	1626.813	7.437	218.75	0.773
8.00	1251.270	6.634	188.61	
7.50	889.977	5.857	151.95	0.534
7.00	557.837	5.115	109.06	
6.50	271.259	4.416	61.43	0.232
6.00	93.998	3.764	24.97	
5.50	176.549	3.163	55.82	0.189
5.00	204.999	2.614	78.42	
4.75	169.905	2.359	72.02	
4.50	107.496	2.117	50.78	0.179
4.25	33.259	1.889	17.61	
4.00	54.547	1.673	32.60	
3.75	69.455	1.471	47.22	
3.50	16.352	1.281	12.77	0.179
3.25	64.856	1.104	58.75	
3.00	94.274	0.941	100.18	
2.75	111.570	0.791	141.05	
2.50	21.126	0.654	32.30	0.294
2.40	22.926	0.602	38.08	
2.30	46.898	0.553	84.81	
2.20	13.560	0.506	26.80	
2.10	57.142	0.461	123.95	
2.00	47.007	0.418	112.46	
1.90	16.346	0.377	43.36	
1.80	40.754	0.339	120.22	
1.70	34.892	0.302	115.54	
1.60	7.202	0.268	26.87	
1.50	21.170	0.235	90.09	0.282
1.40	11.976	0.205	58.42	
1.30	9.378	0.177	52.98	
1.20	15.258	0.151	101.05	
1.10	8.870	0.127	69.84	
1.00	8.476	0.105	80.72	

Table 3-25 Weighing factor (steepness 1/25, 90°)

90°	Steepness 1/25		Transfer function	Weighing factor
T	BS	Hs		
10.00	1392.544	5.920	235.23	
9.50	1191.226	5.424	219.62	0.608
9.00	985.026	4.929	199.84	
8.50	774.217	4.440	174.37	0.480
8.00	562.292	3.960	141.99	
7.50	351.373	3.497	100.48	0.284
7.00	192.735	3.054	63.11	
6.50	192.878	2.636	73.17	0.258
6.00	316.713	2.247	140.95	
5.50	428.654	1.888	227.04	0.610
5.00	450.657	1.561	288.70	
4.75	405.754	1.409	287.97	
4.50	321.507	1.264	254.36	0.598
4.25	200.413	1.128	177.67	
4.00	64.182	0.999	64.25	
3.75	121.003	0.878	137.82	
3.50	193.191	0.765	252.54	0.402
3.25	143.256	0.659	217.38	
3.00	27.966	0.562	49.76	
2.75	118.692	0.472	251.47	
2.50	53.046	0.390	136.02	0.510
2.40	98.760	0.360	274.33	
2.30	53.646	0.330	162.56	
2.20	60.156	0.302	199.19	
2.10	58.180	0.275	211.56	
2.00	45.008	0.250	180.03	
1.90	23.038	0.225	102.39	
1.80	44.766	0.202	221.61	
1.70	42.349	0.180	235.27	
1.60	38.620	0.160	241.38	
1.50	18.814	0.140	134.39	0.572
1.40	16.276	0.122	133.41	
1.30	14.324	0.106	135.13	
1.20	20.350	0.090	226.11	
1.10	22.078	0.076	290.50	
1.00	22.242	0.062	358.74	

Table 3-26 Weighing factor (steepness 1/20, 90°)

90°	Steepness 1/20		Transfer function	Weighing factor
T	BS	Hs		
10.00	1831.367	7.400	247.48	
9.50	1557.955	6.780	229.79	0.640
9.00	1280.816	6.161	207.89	
8.50	999.913	5.550	180.16	0.498
8.00	716.283	4.950	144.70	
7.50	446.066	4.371	102.05	0.289
7.00	239.459	3.817	62.73	
6.50	241.181	3.295	73.20	0.260
6.00	399.662	2.809	142.28	
5.50	537.809	2.361	227.79	0.615
5.00	561.646	1.951	287.88	
4.75	502.875	1.761	285.56	
4.50	399.819	1.580	253.05	0.597
4.25	248.615	1.410	176.32	
4.00	78.855	1.249	63.13	
3.75	150.511	1.097	137.20	
3.50	240.328	0.956	251.39	0.401
3.25	177.470	0.824	215.38	
3.00	34.439	0.702	49.06	
2.75	147.334	0.590	249.72	
2.50	65.474	0.488	134.17	0.508
2.40	121.526	0.449	270.66	
2.30	65.575	0.413	158.78	
2.20	75.242	0.378	199.05	
2.10	72.582	0.344	210.99	
2.00	55.824	0.312	178.92	
1.90	28.148	0.282	99.82	
1.80	56.090	0.253	221.70	
1.70	52.772	0.226	233.50	
1.60	47.550	0.200	237.75	
1.50	23.382	0.176	132.85	0.570
1.40	20.500	0.153	133.99	
1.30	17.392	0.132	131.76	
1.20	24.612	0.112	219.75	
1.10	27.292	0.094	290.34	
1.00	27.834	0.078	356.85	

Table 3-27 Weighing factor (steepness 1/15, 90°)

90°	Steepness 1/15		Transfer function	Weighing factor
T	BS	Hs		
10.00	2647.941	9.916	267.04	
9.50	2232.774	9.085	245.76	0.695
9.00	1818.108	8.256	220.22	
8.50	1401.359	7.437	188.43	0.529
8.00	990.273	6.634	149.27	
7.50	605.061	5.857	103.31	0.297
7.00	310.916	5.115	60.79	
6.50	324.625	4.416	73.51	0.266
6.00	549.272	3.764	145.93	
5.50	727.529	3.163	230.01	0.624
5.00	737.603	2.614	282.17	
4.75	664.157	2.359	281.54	
4.50	532.720	2.117	251.64	0.598
4.25	329.603	1.889	174.49	
4.00	102.145	1.673	61.05	
3.75	199.711	1.471	135.77	
3.50	319.707	1.281	249.58	0.402
3.25	233.088	1.104	211.13	
3.00	45.236	0.941	48.07	
2.75	197.634	0.791	249.85	
2.50	84.034	0.654	128.49	0.508
2.40	160.268	0.602	266.23	
2.30	86.191	0.553	155.86	
2.20	99.740	0.506	197.11	
2.10	95.586	0.461	207.34	
2.00	72.928	0.418	174.47	
1.90	37.426	0.377	99.27	
1.80	72.758	0.339	214.63	
1.70	69.692	0.302	230.77	
1.60	64.072	0.268	239.07	
1.50	31.294	0.235	133.17	0.570
1.40	27.522	0.205	134.25	
1.30	22.840	0.177	129.04	
1.20	32.370	0.151	214.37	
1.10	35.844	0.127	282.24	
1.00	36.891	0.105	351.34	

Table 3-28 Fatigue damage (0 degree)

4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.24	0.00	0.00
3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	7.03	0.00	0.00
3.25	0.00	0.00	0.00	0.00	0.00	0.00	5.28	4.58	0.00	0.00
2.75	0.00	0.00	0.00	0.00	0.00	0.00	16.00	2.77	0.00	0.00
2.25	0.00	0.00	0.00	0.00	0.00	12.43	59.58	0.00	0.00	0.00
1.75	0.00	0.00	0.00	0.00	1.19	160.78	32.16	0.71	0.00	0.00
1.25	0.00	0.00	0.00	0.56	106.77	139.91	0.30	0.00	0.00	0.00
0.75	0.00	0.00	0.00	84.98	106.97	4.14	0.00	0.00	0.00	0.00
0.25	0.00	0.01	0.63	5.63	0.58	0.00	0.00	0.00	0.00	0.00
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-29 Fatigue damage (45 degree)

4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.25	0.00	0.00	0.00	0.00	0.00	4.14	7.01	0.00	0.00	0.00
1.75	0.00	0.00	0.00	0.00	0.00	7.80	2.47	0.00	0.00	0.00
1.25	0.00	0.00	0.00	1.67	10.85	12.43	0.00	0.00	0.00	0.00
0.75	0.00	0.00	0.34	18.92	15.94	0.38	0.00	0.00	0.00	0.00
0.25	0.00	0.01	0.52	2.56	0.16	0.00	0.00	0.00	0.00	0.00
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-30 Fatigue damage (90 degree)

4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.75	0.00	0.00	0.00	0.00	0.00	0.00	0.82	0.00	0.00	0.00
1.25	0.00	0.00	0.00	0.00	0.43	0.36	0.00	0.00	0.00	0.00
0.75	0.00	0.00	0.00	2.65	1.88	0.15	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.17	0.90	0.10	0.00	0.00	0.00	0.00	0.00
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-31 Weighted fatigue damage (0 degree)

4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	5.24	0.00	0.00
3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.60	0.00	0.00
3.25	0.00	0.00	0.00	0.00	0.00	0.00	1.13	2.34	0.00	0.00
2.75	0.00	0.00	0.00	0.00	0.00	0.00	3.43	1.42	0.00	0.00
2.25	0.00	0.00	0.00	0.00	0.00	0.30	12.78	0.00	0.00	0.00
1.75	0.00	0.00	0.00	0.00	0.06	3.89	6.90	0.37	0.00	0.00
1.25	0.00	0.00	0.00	0.06	5.38	3.39	0.06	0.00	0.00	0.00
0.75	0.00	0.00	0.00	8.60	5.39	0.10	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.03	0.57	0.03	0.00	0.00	0.00	0.00	0.00
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-32 Weighted fatigue damage (45 degree)

4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.25	0.00	0.00	0.00	0.00	0.00	0.04	0.13	0.00	0.00	0.00
1.75	0.00	0.00	0.00	0.00	0.00	0.07	0.04	0.00	0.00	0.00
1.25	0.00	0.00	0.00	0.01	0.08	0.11	0.00	0.00	0.00	0.00
0.75	0.00	0.00	0.01	0.13	0.12	0.00	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

Table 3-33 Weighted fatigue damage (90 degree)

4.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
3.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.75	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
2.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1.75	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00
1.25	0.00	0.00	0.00	0.00	0.09	0.08	0.00	0.00	0.00	0.00
0.75	0.00	0.00	0.00	0.17	0.40	0.04	0.00	0.00	0.00	0.00
0.25	0.00	0.00	0.02	0.06	0.02	0.00	0.00	0.00	0.00	0.00
Hs / Tp	0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5

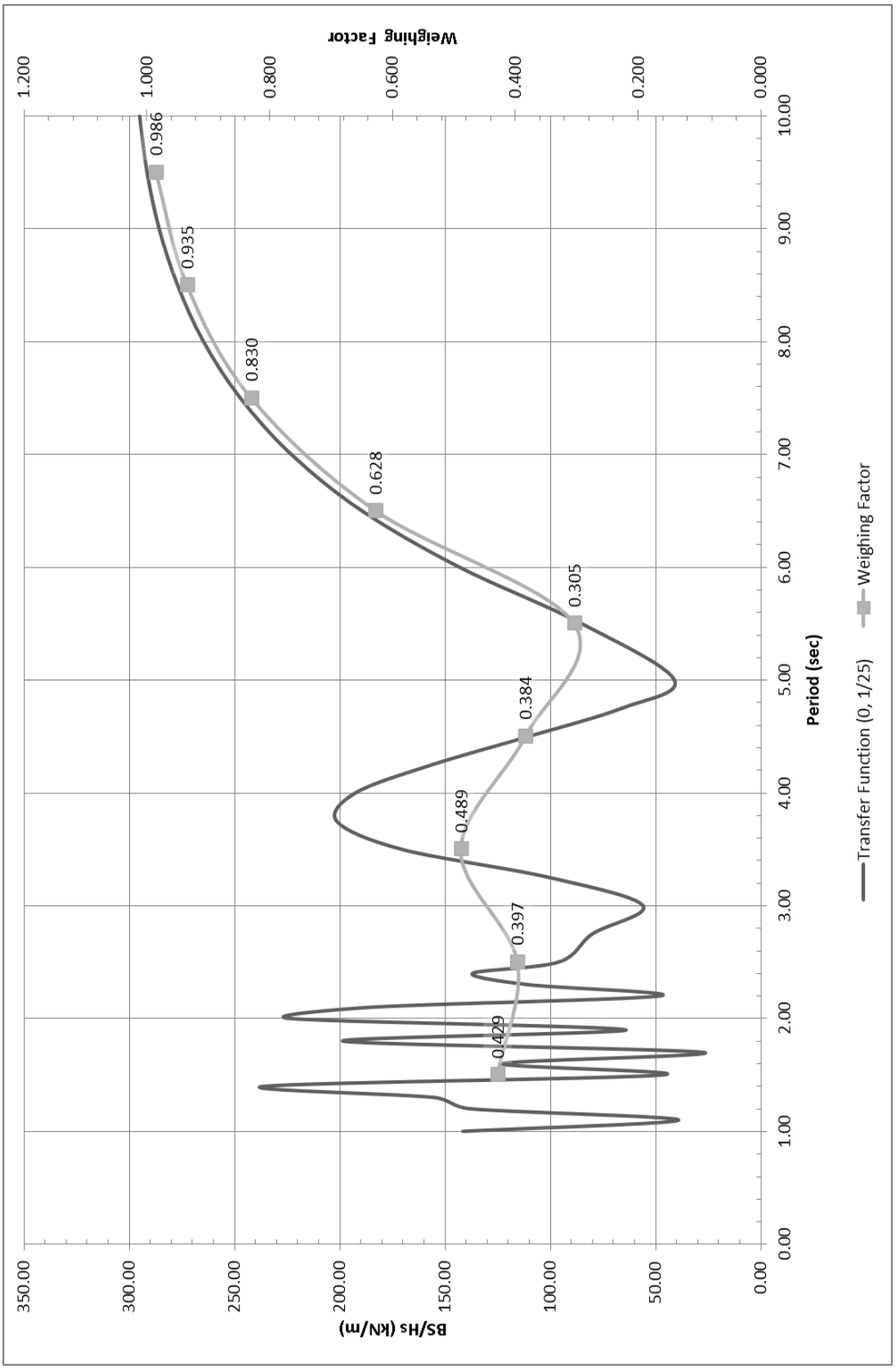

Figure 3-39 Static Transfer Function (0°,1/25)

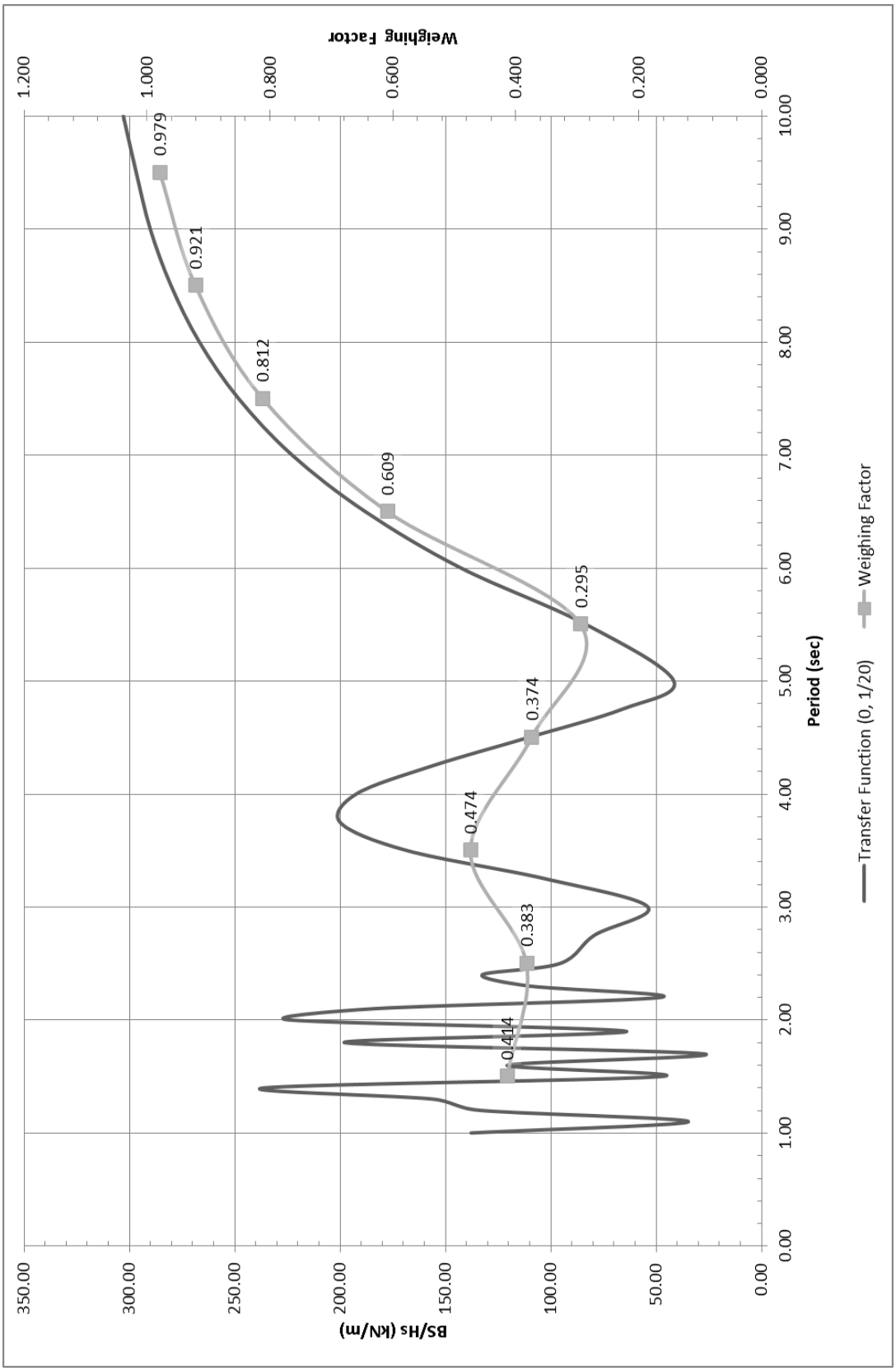

Figure 3-40 Static Transfer Function (0°,1/20)

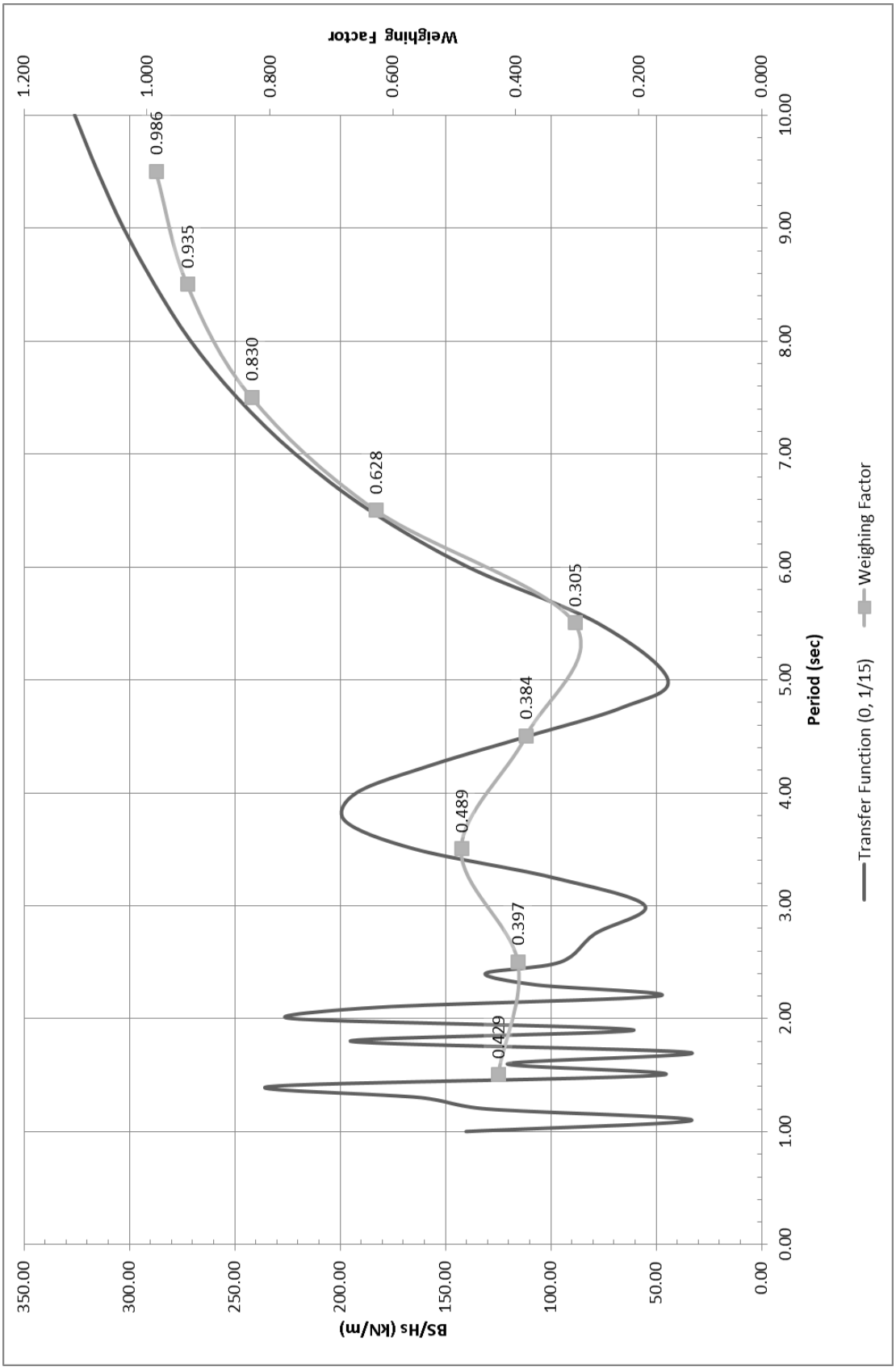

Figure 3-41 Static Transfer Function (0°,1/15)

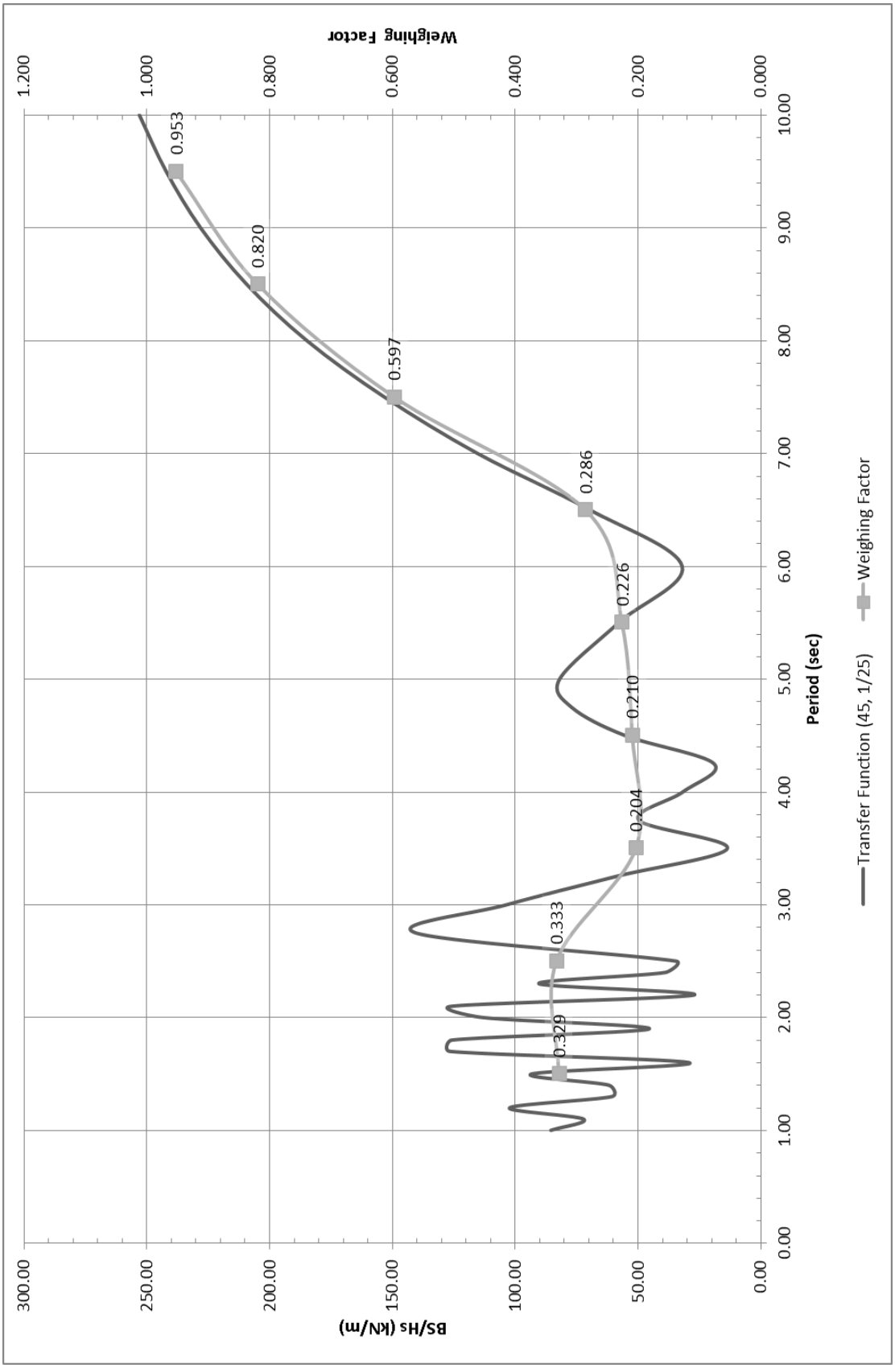

Figure 3-42 Static Transfer Function (45°,1/25)

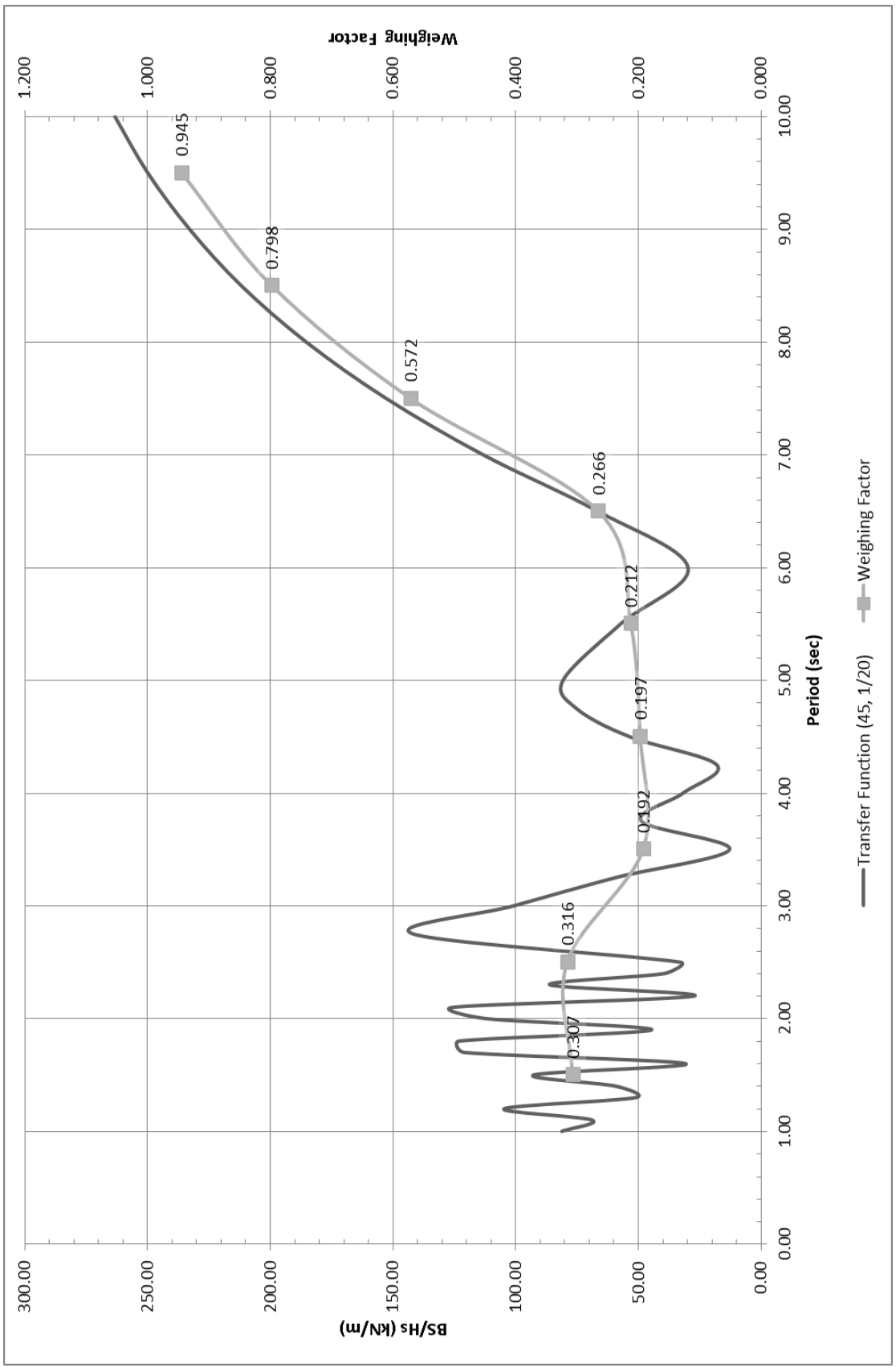

Figure 3-43 Static Transfer Function (45°,1/20)

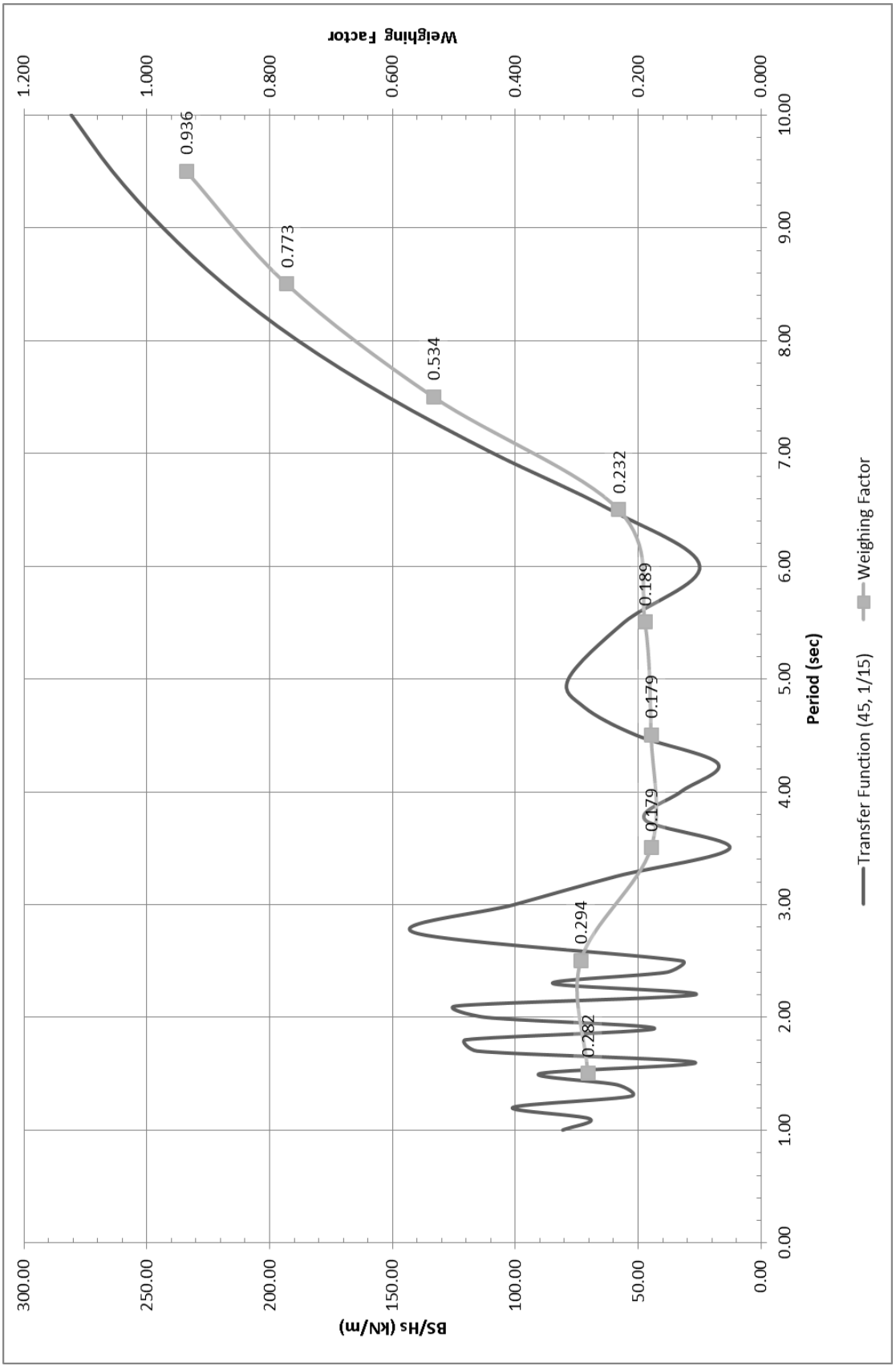

Figure 3-44 Static Transfer Function (45°,1/15)

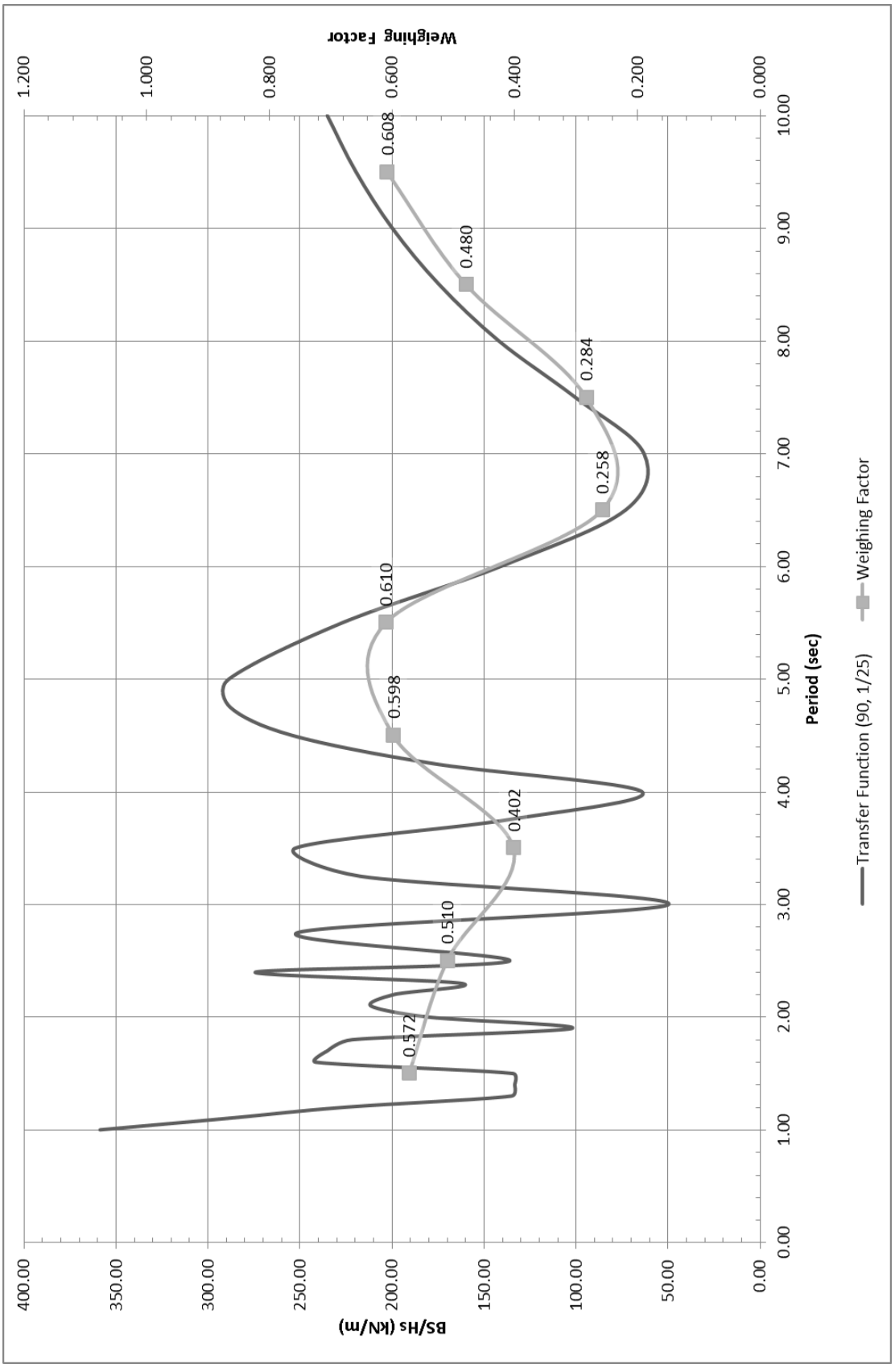

Figure 3-45 Static Transfer Function (90°,1/25)

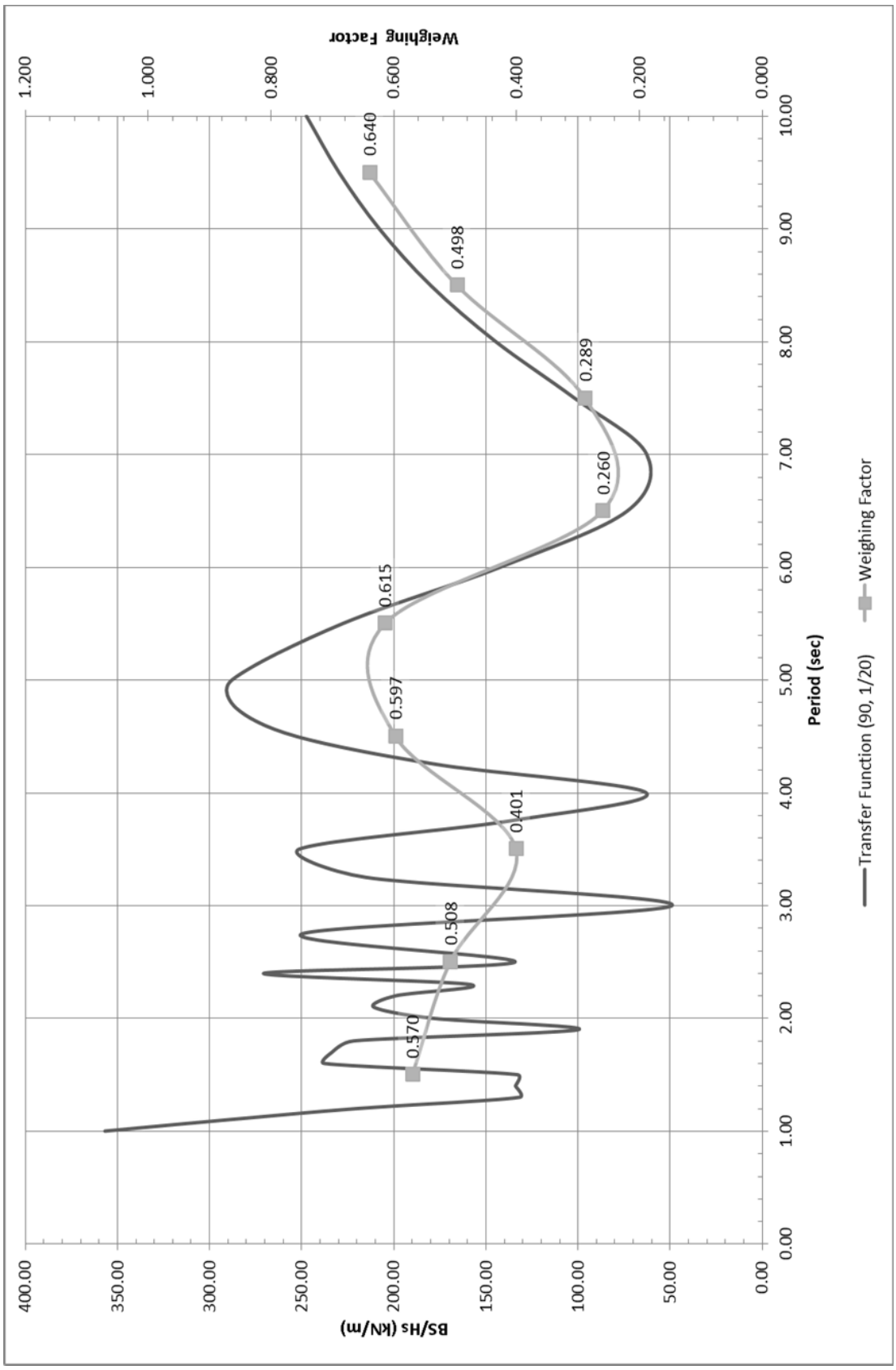

Figure 3-46 Static Transfer Function (90°,1/20)

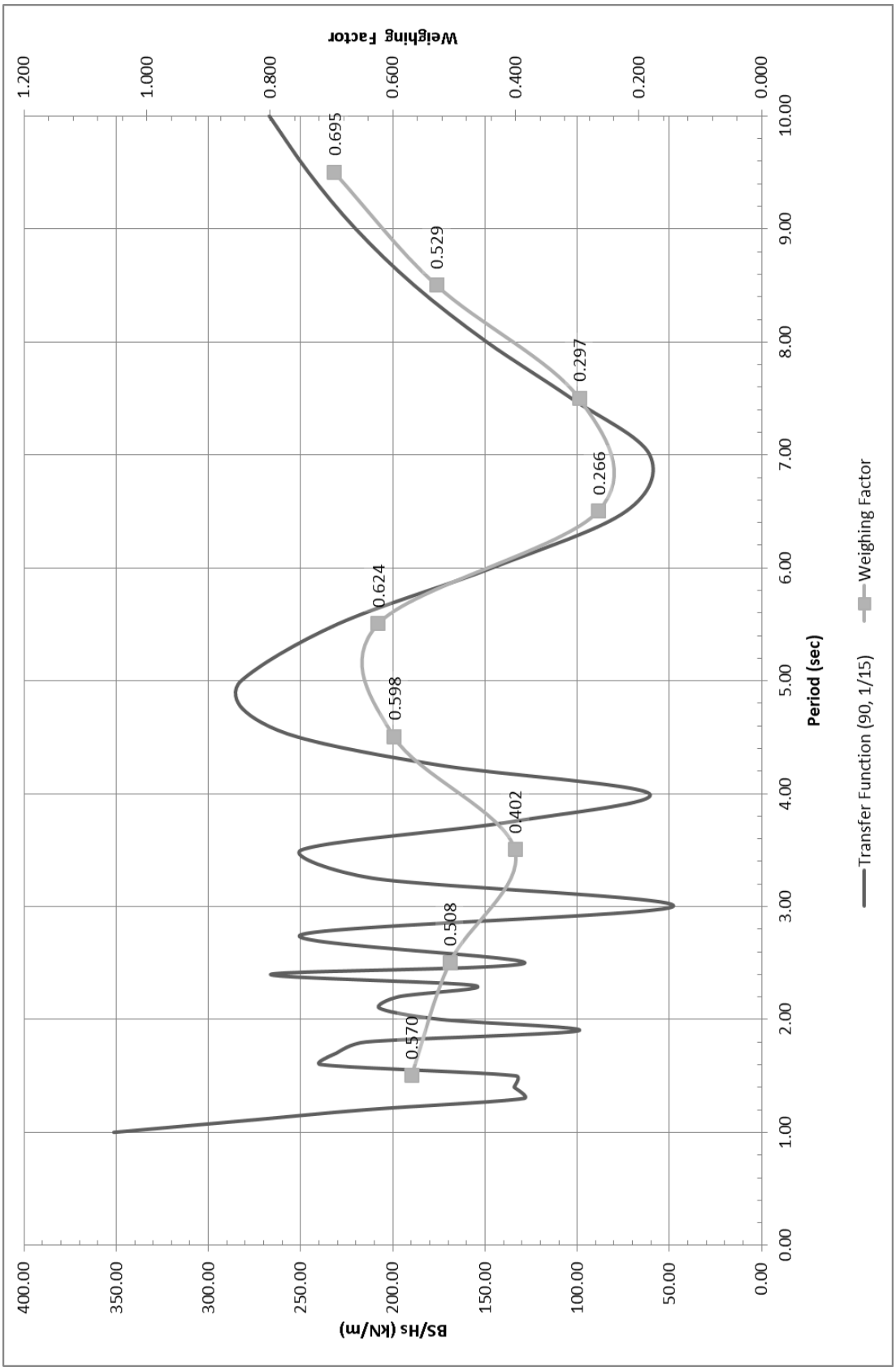

Figure 3-47 Static Transfer Function (90°,1/15)

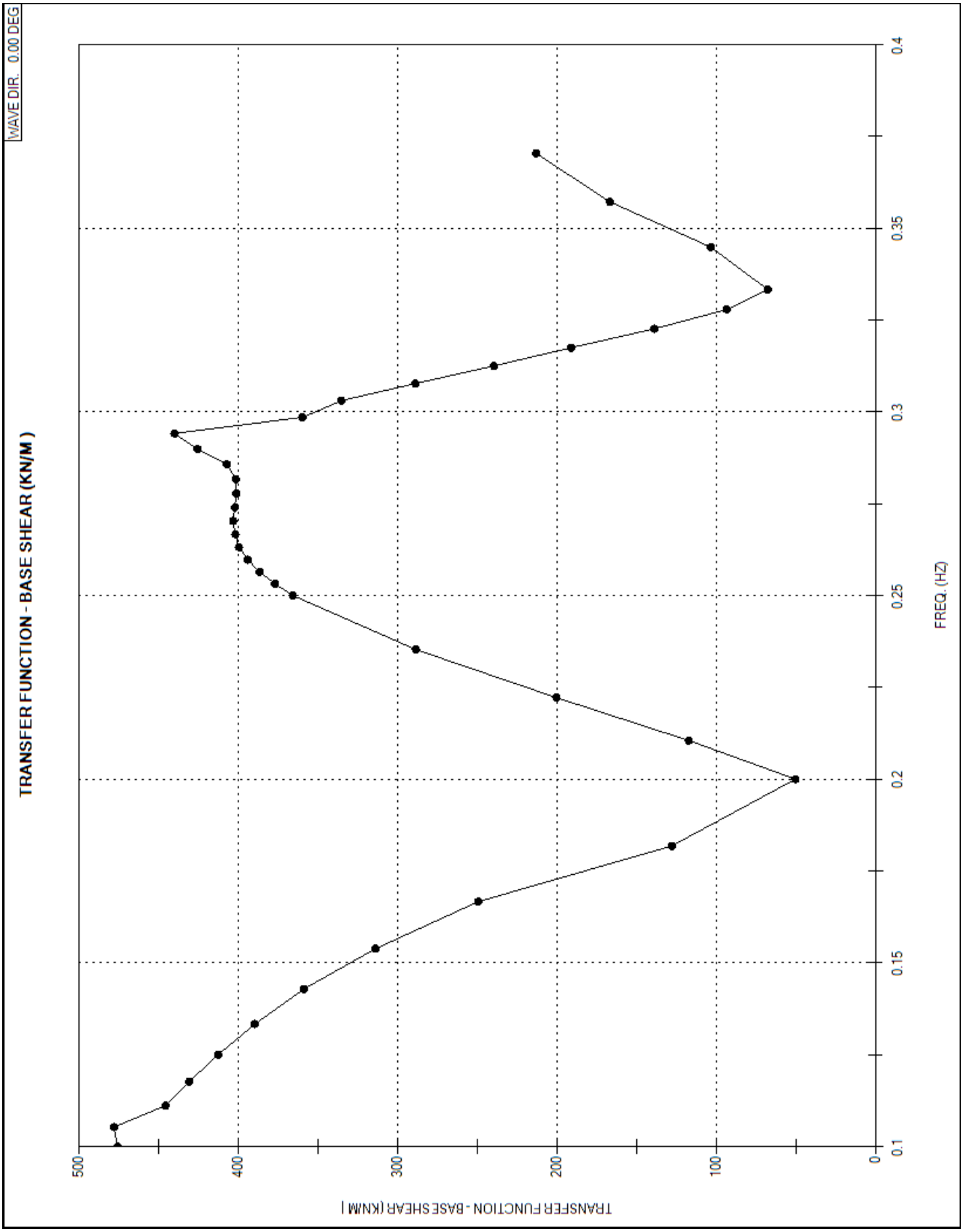

Figure 3-48 Dynamic Transfer Function (0°, 1/16)

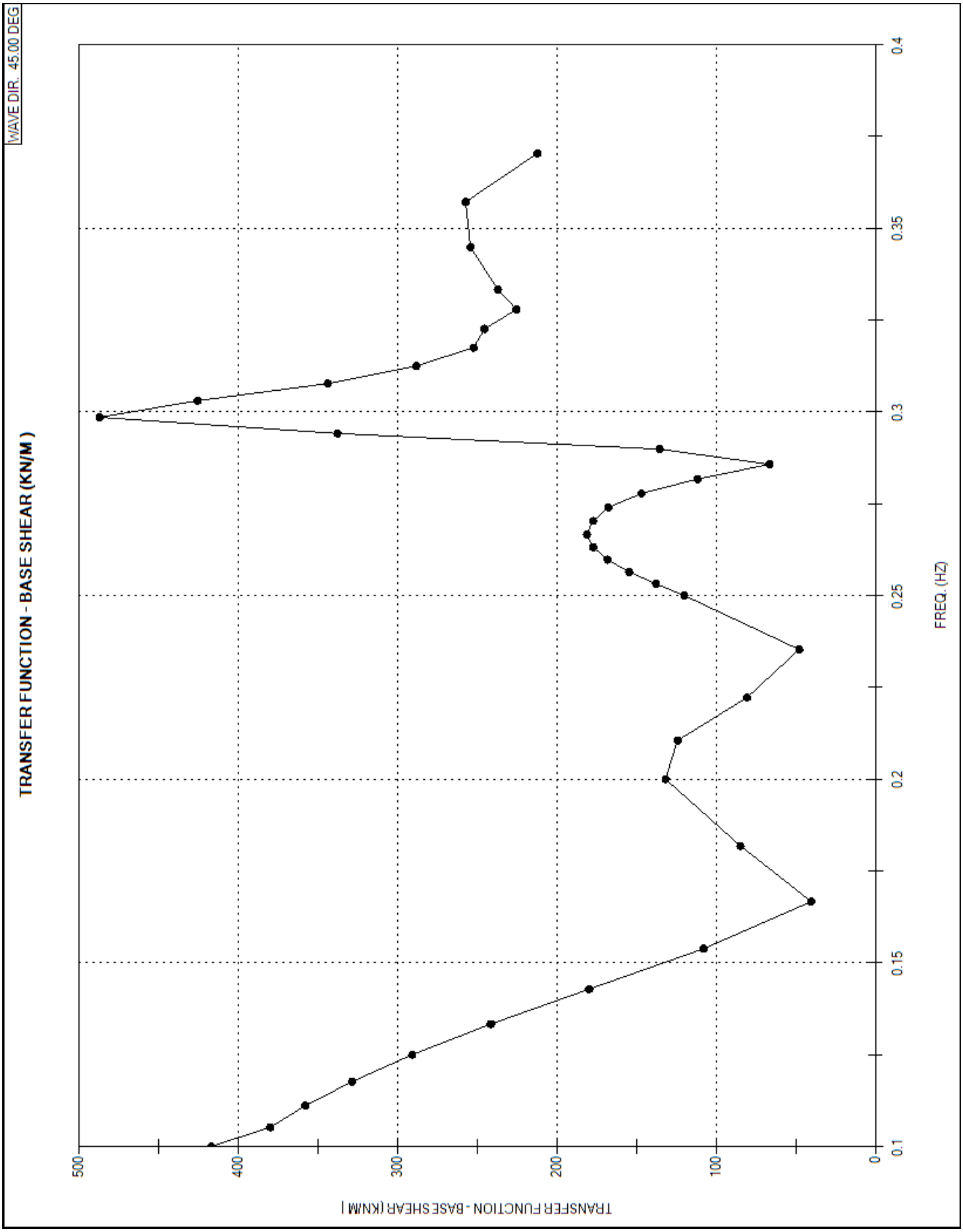

Figure 3-49 Dynamic Transfer Function (45°, 1/16)

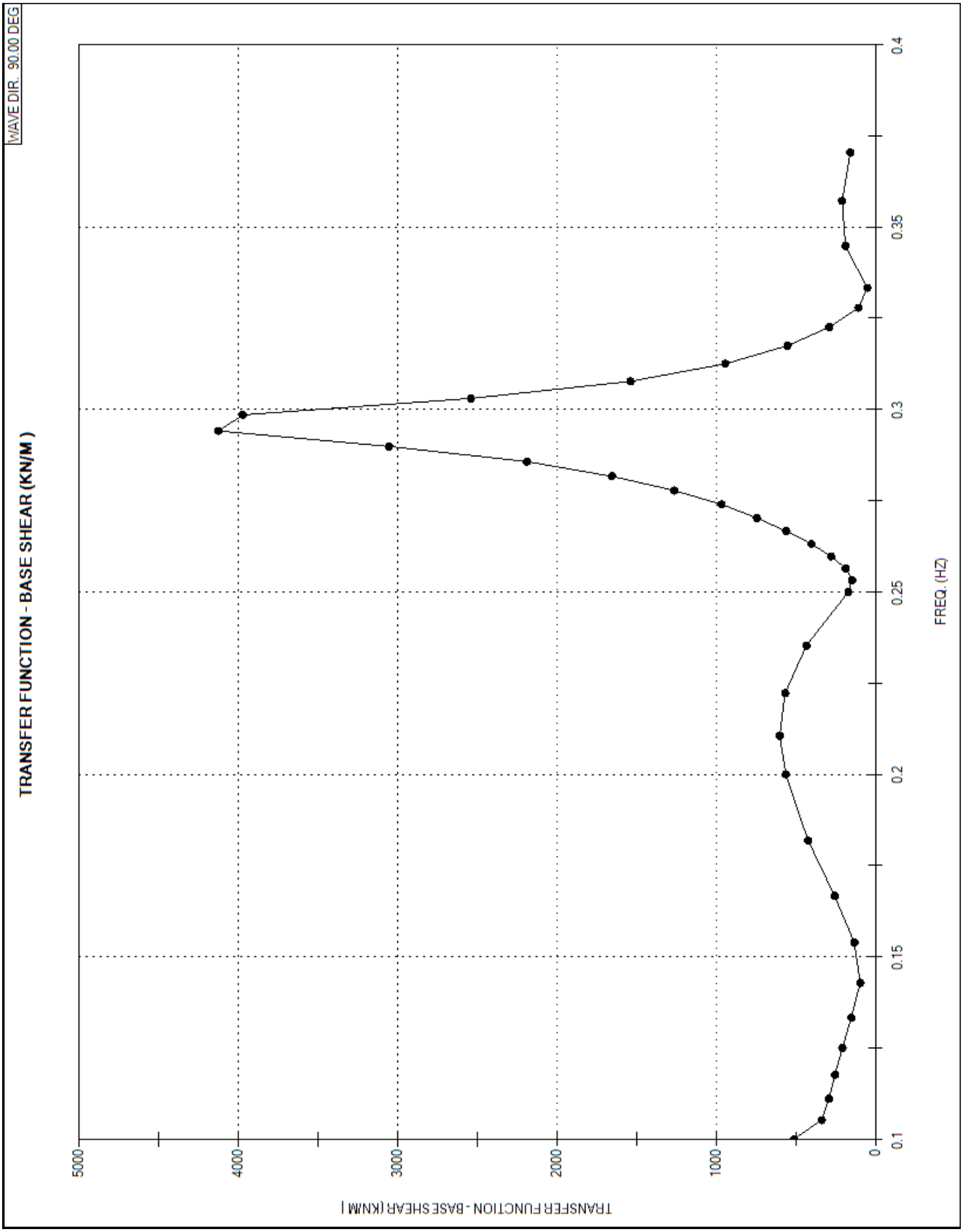

Figure 3-50 Dynamic Transfer Function (90°, 1/16)

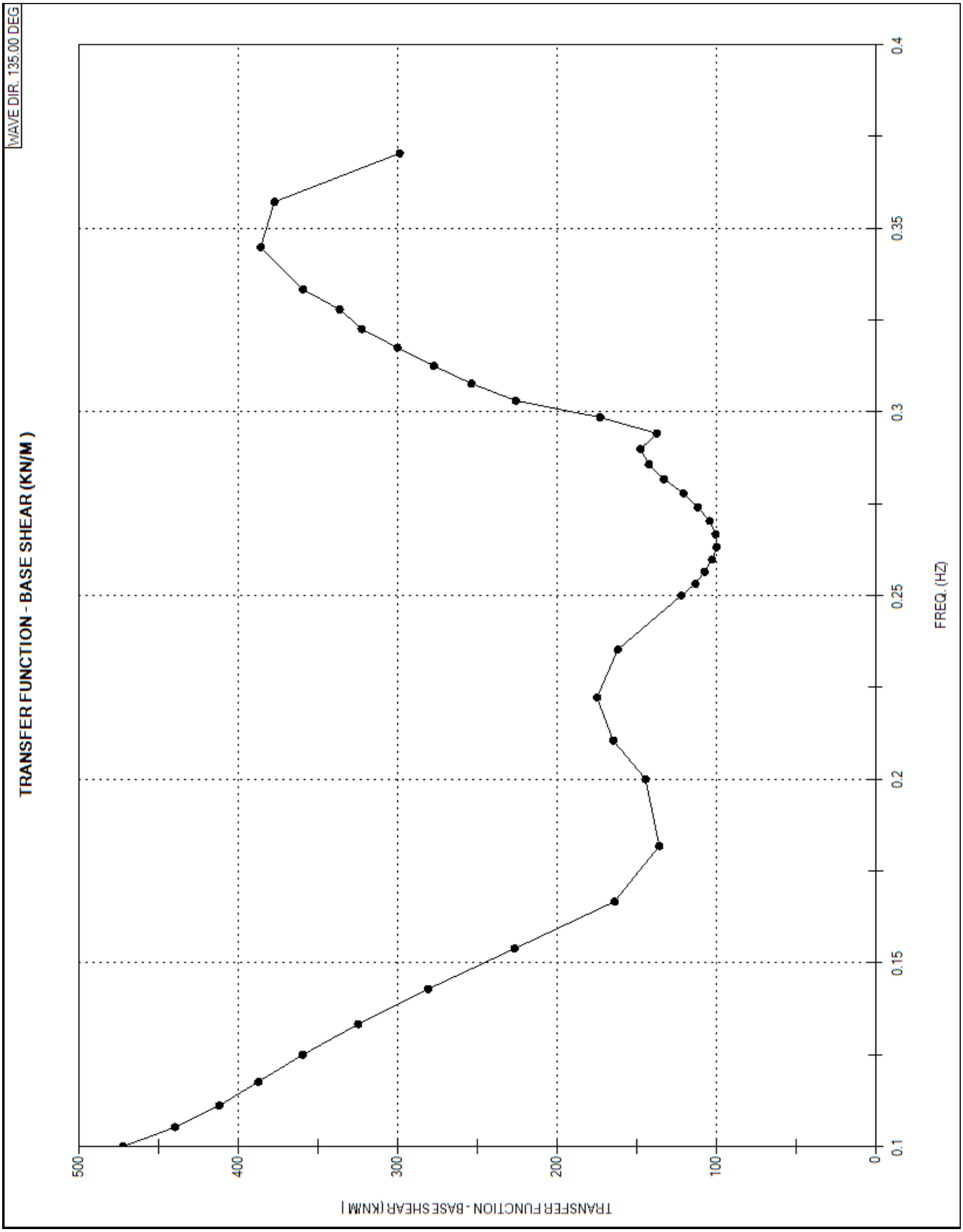

Figure 3-51 Dynamic Transfer Function (135°, 1/16)

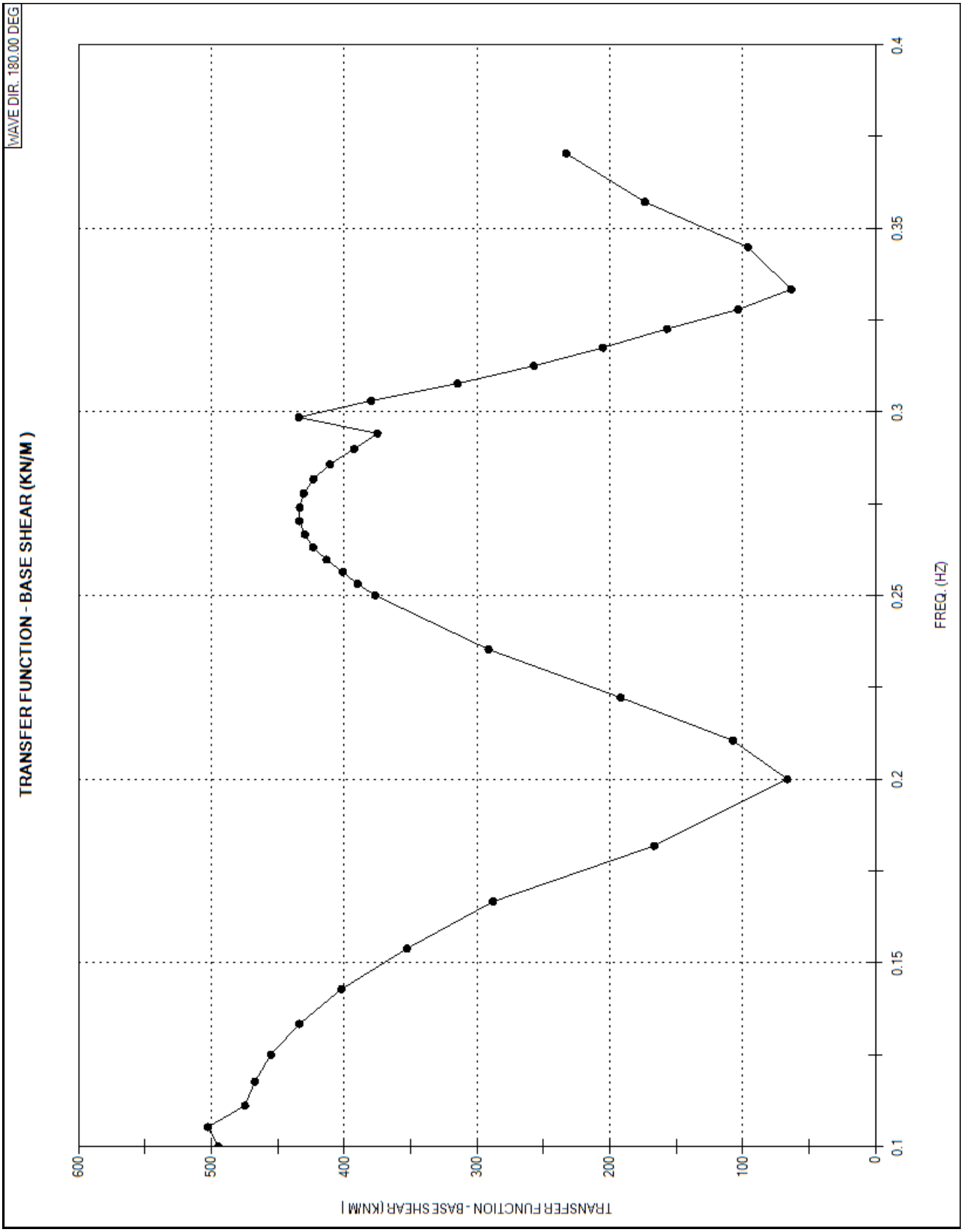

Figure 3-52 Dynamic Transfer Function (180°, 1/16)

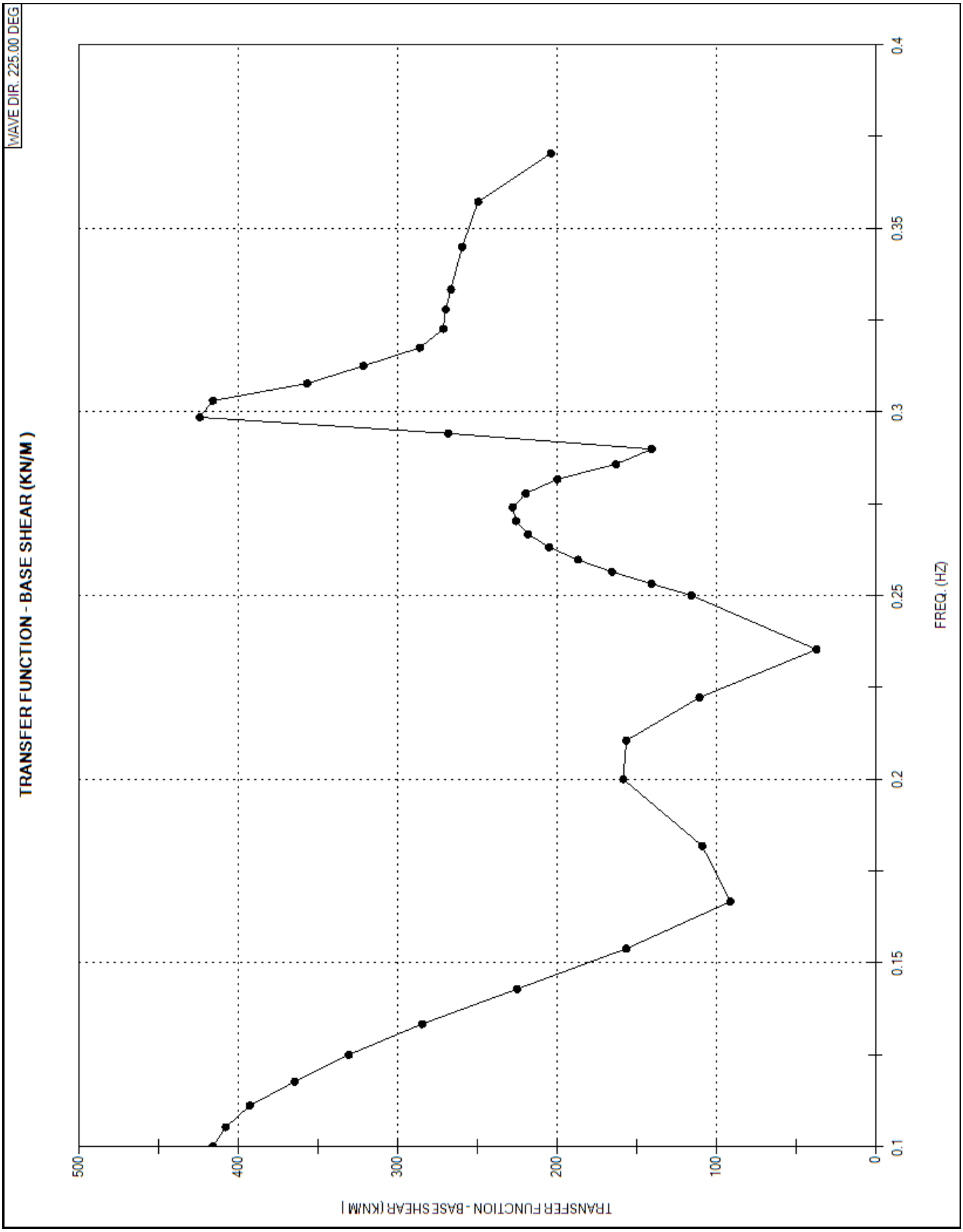

Figure 3-53 Dynamic Transfer Function (225°, 1/16)

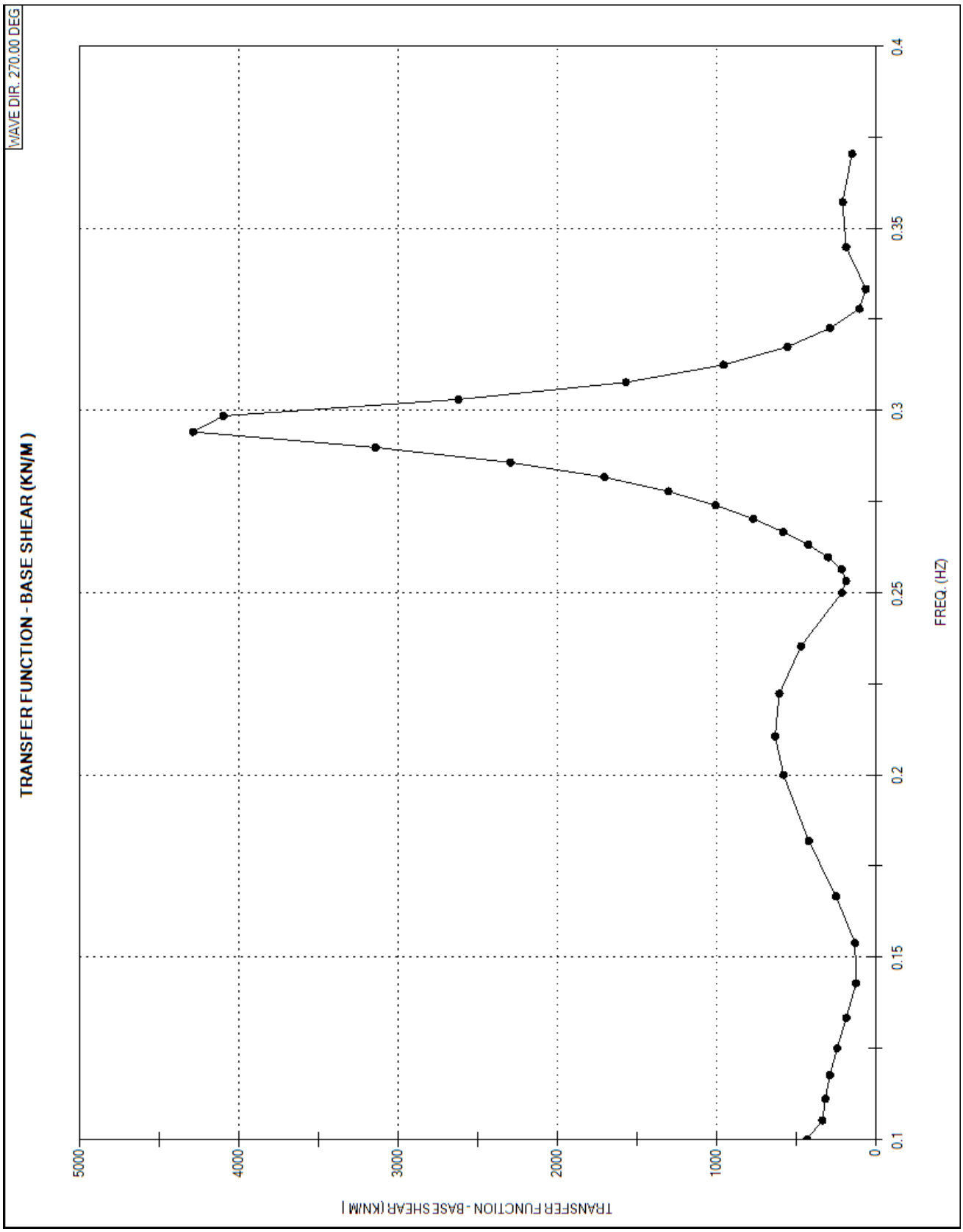

Figure 3-54 Dynamic Transfer Function (270°, 1/16)

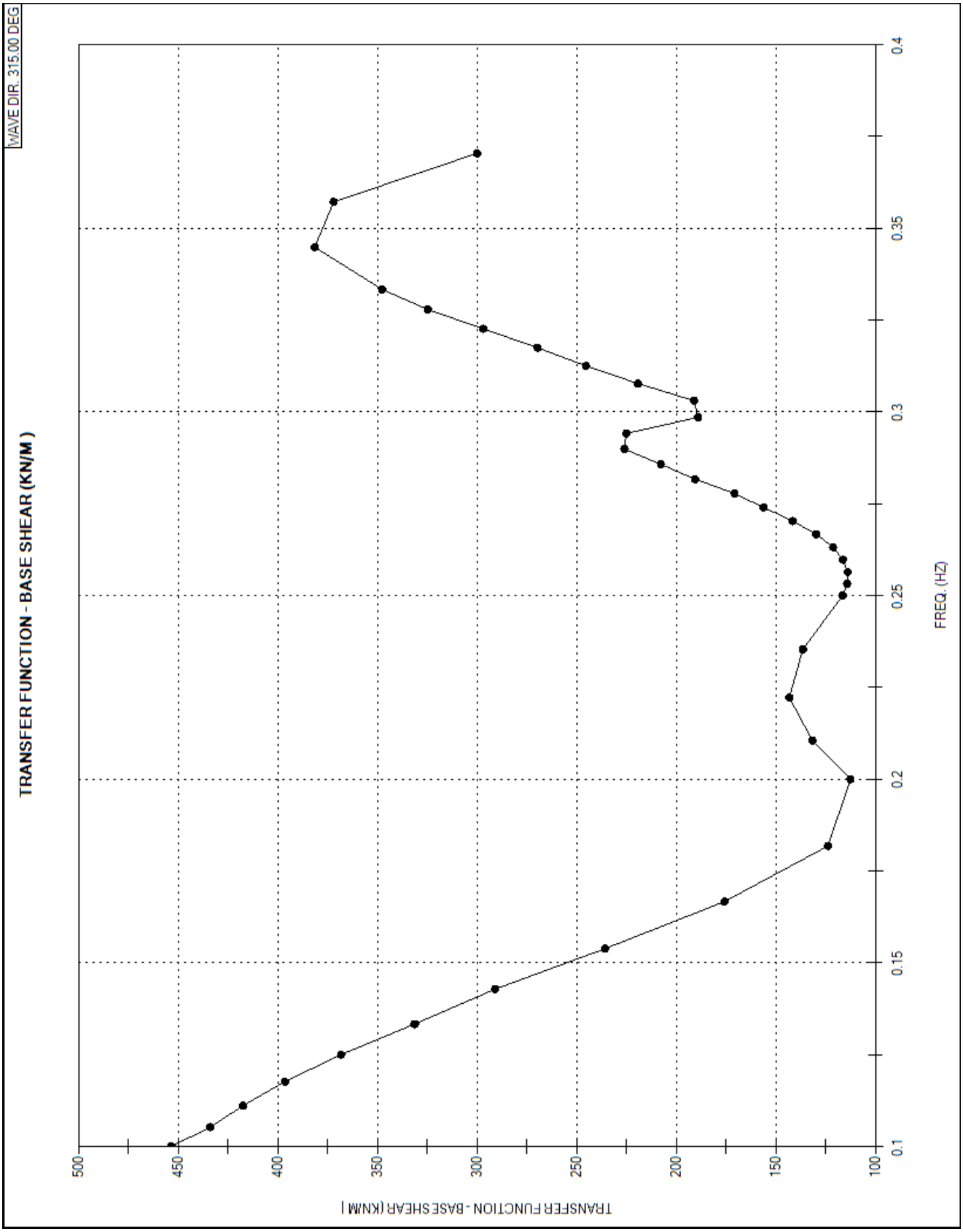

Figure 3-55 Dynamic Transfer Function (315°, 1/16)

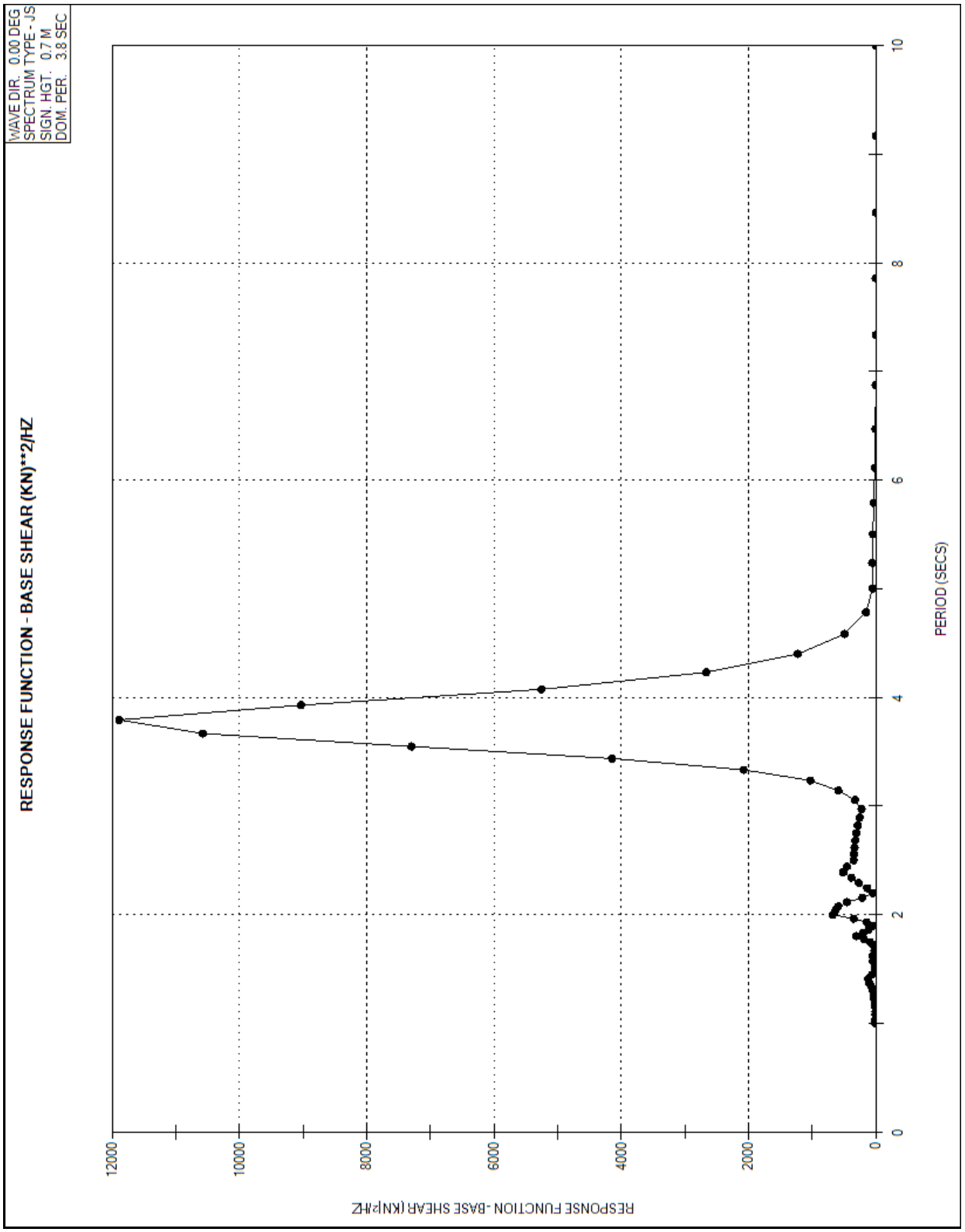

Figure 3-56 Response function (0°, 1/15)

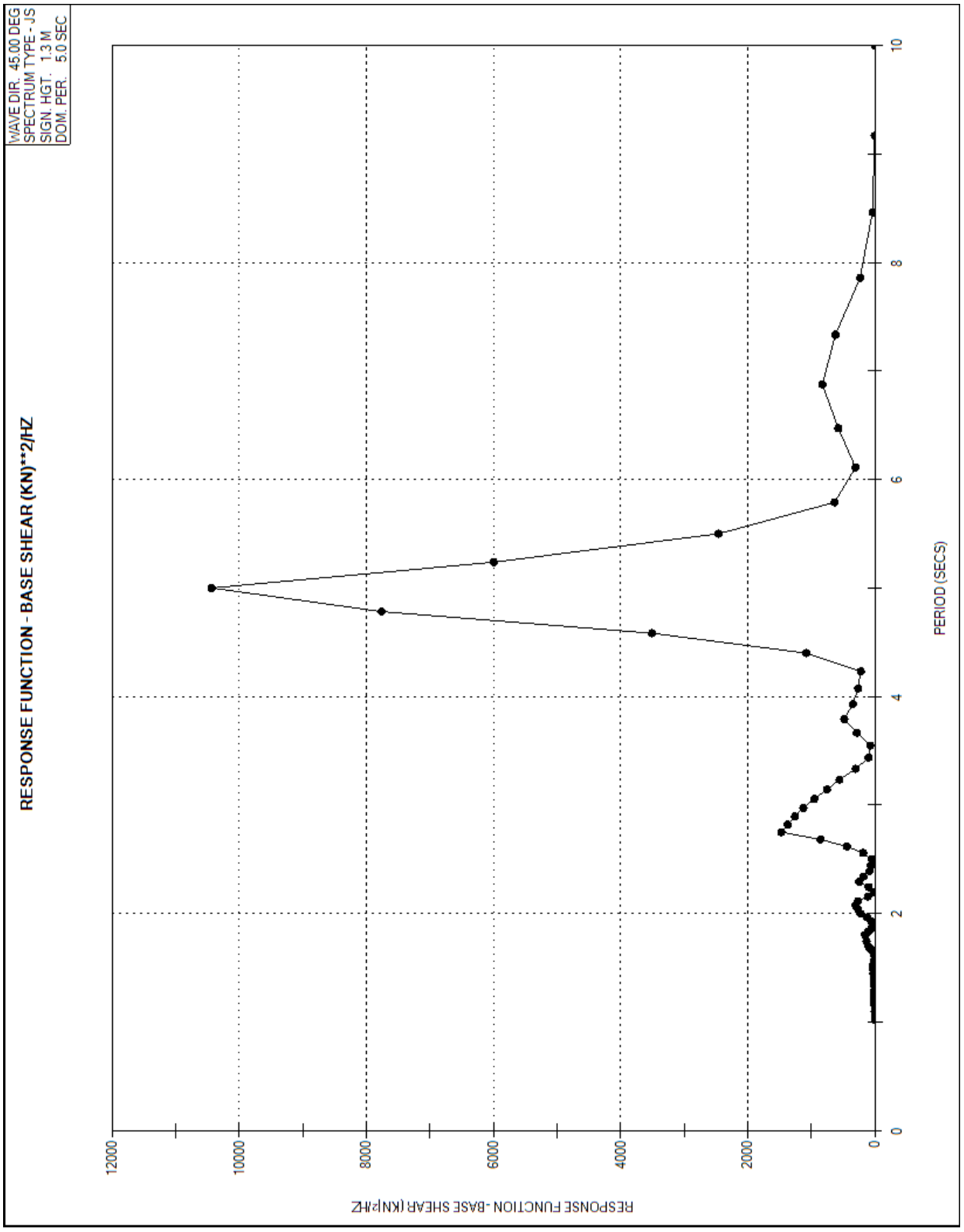

Figure 3-57 Response function (45°, 1/15)

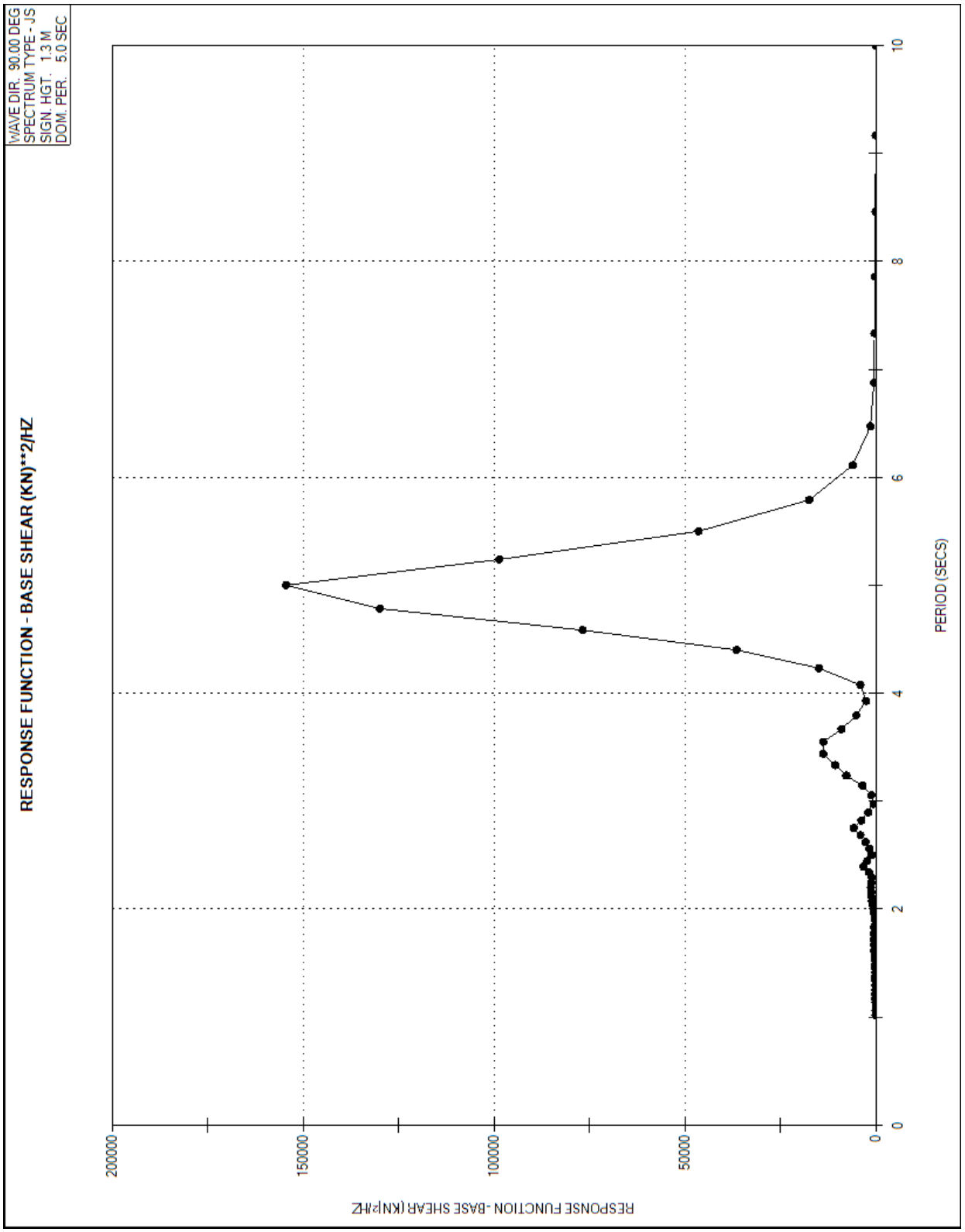

Figure 3-58 Response function (90°, 1/15)

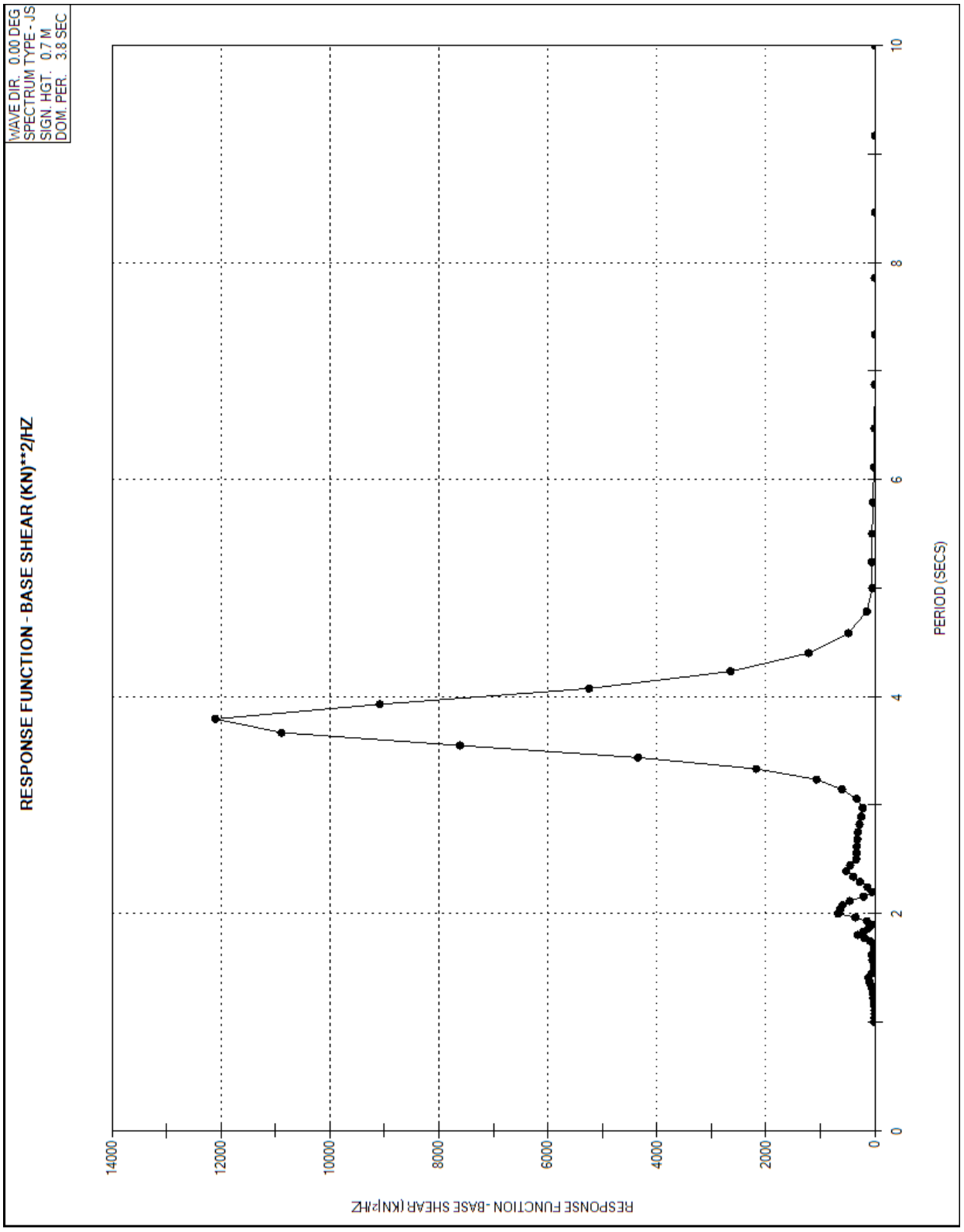

Figure 3-59 Response function (0°, 1/20)

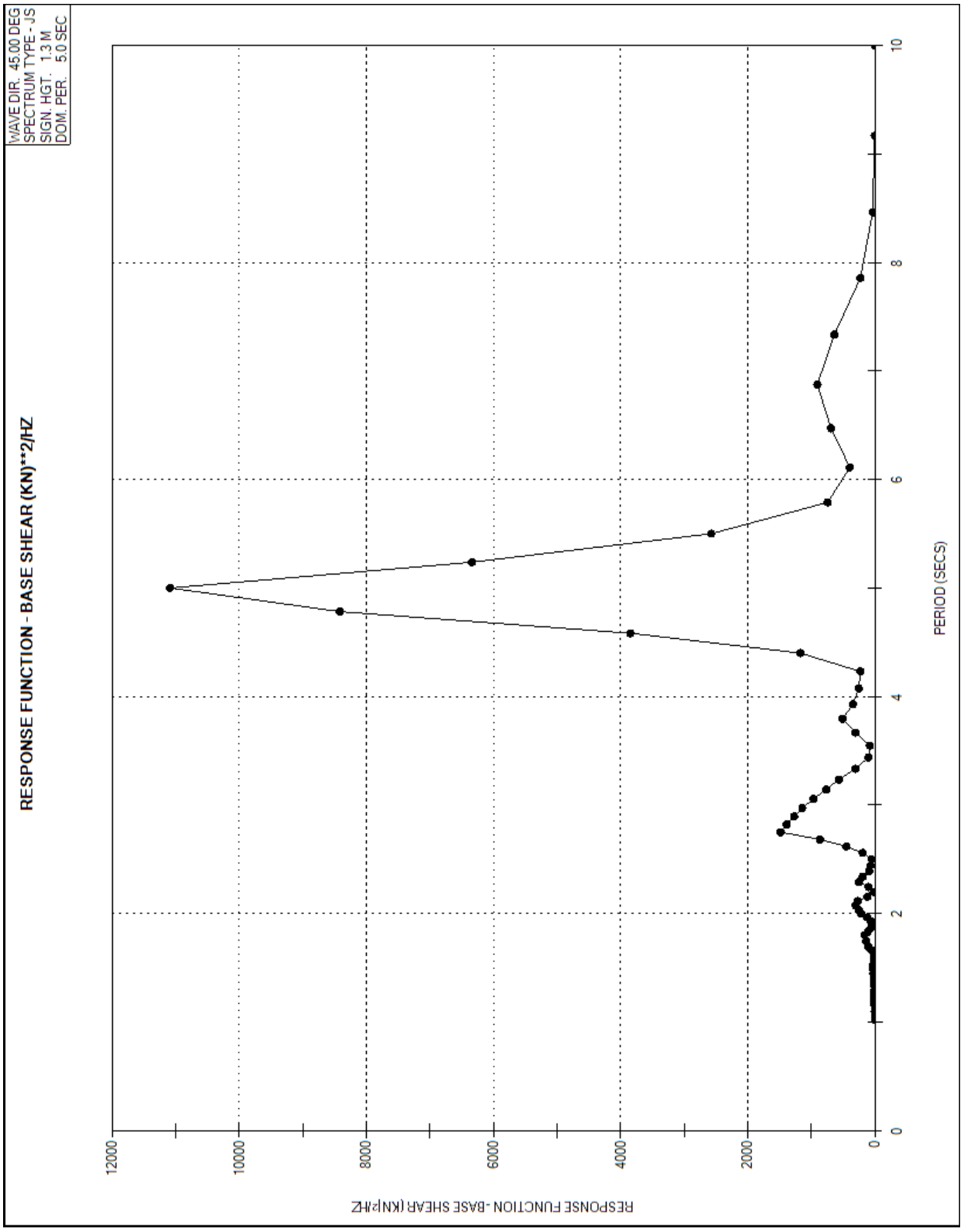

Figure 3-60 Response function (45°, 1/20)

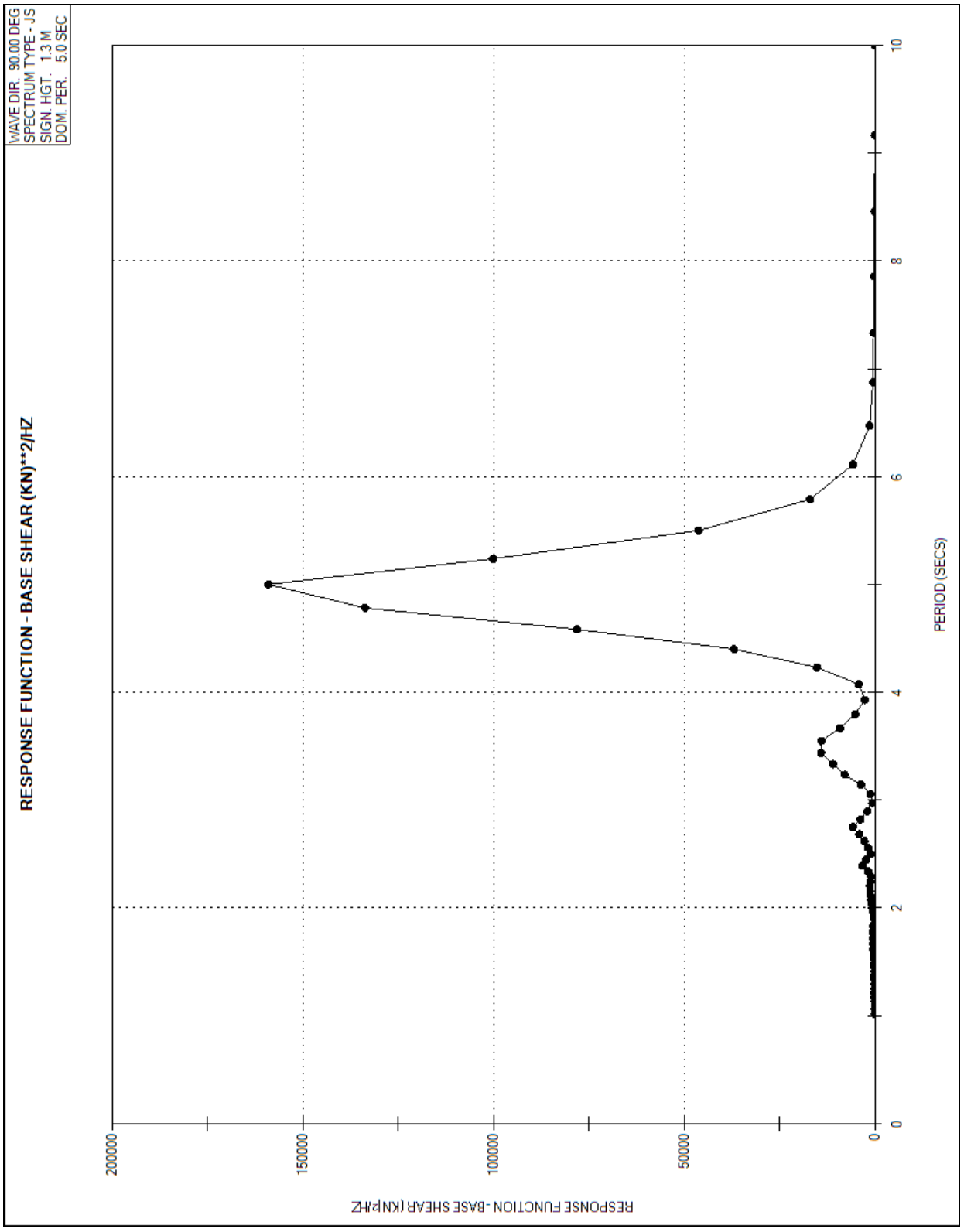

Figure 3-61 Response function (90°, 1/20)

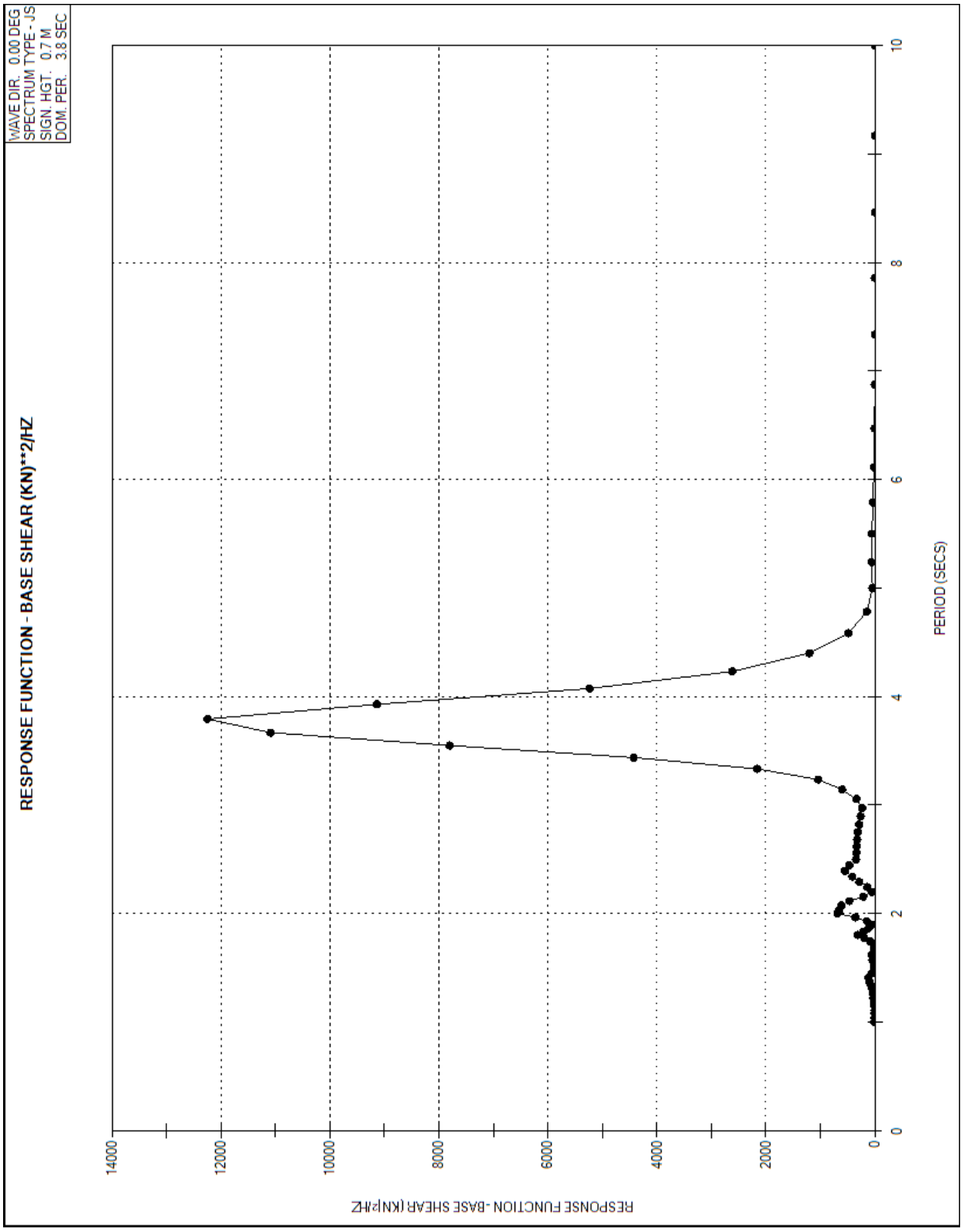

Figure 3-62 Response function (0°, 1/25)

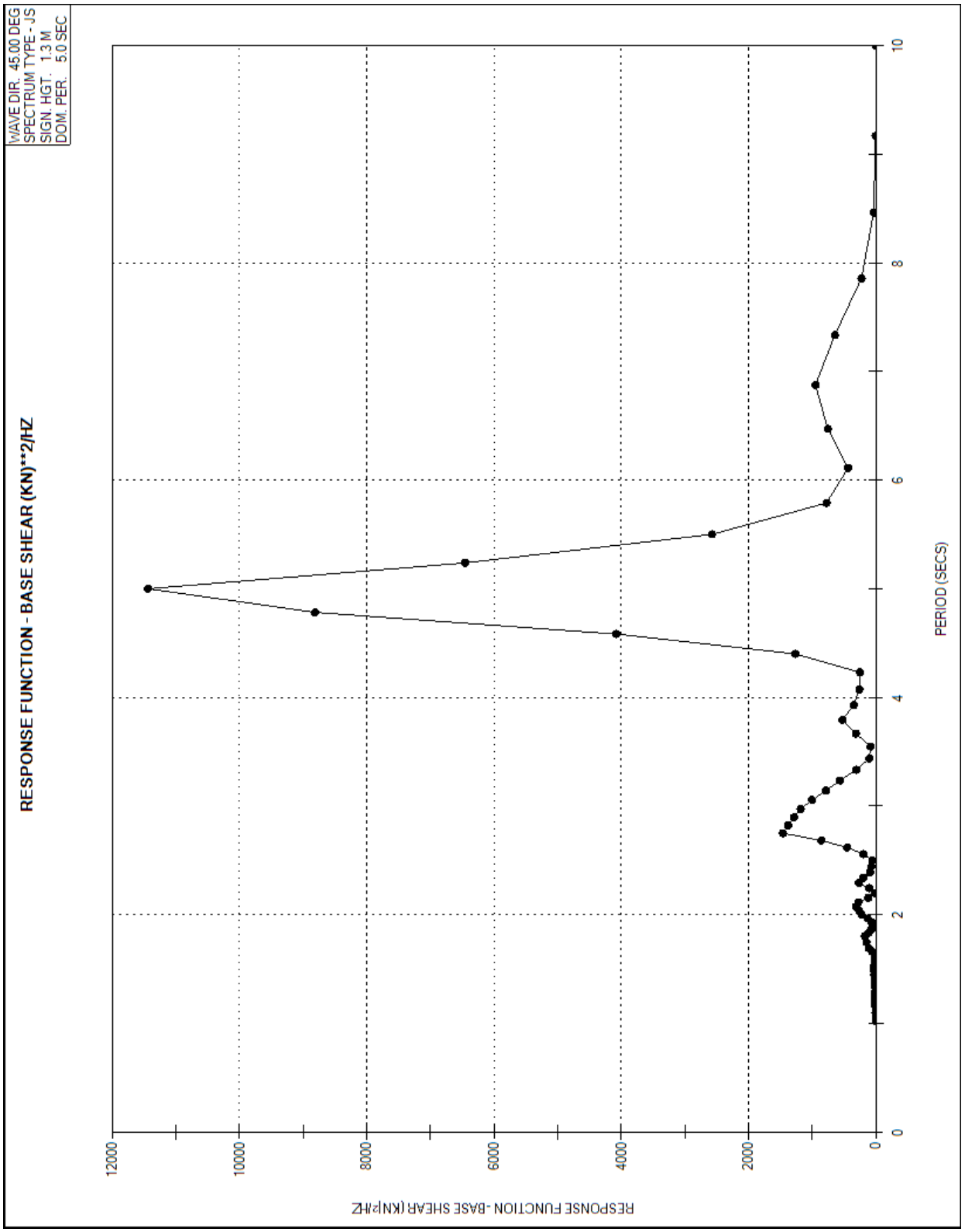

Figure 3-63 Response function (45°, 1/25)

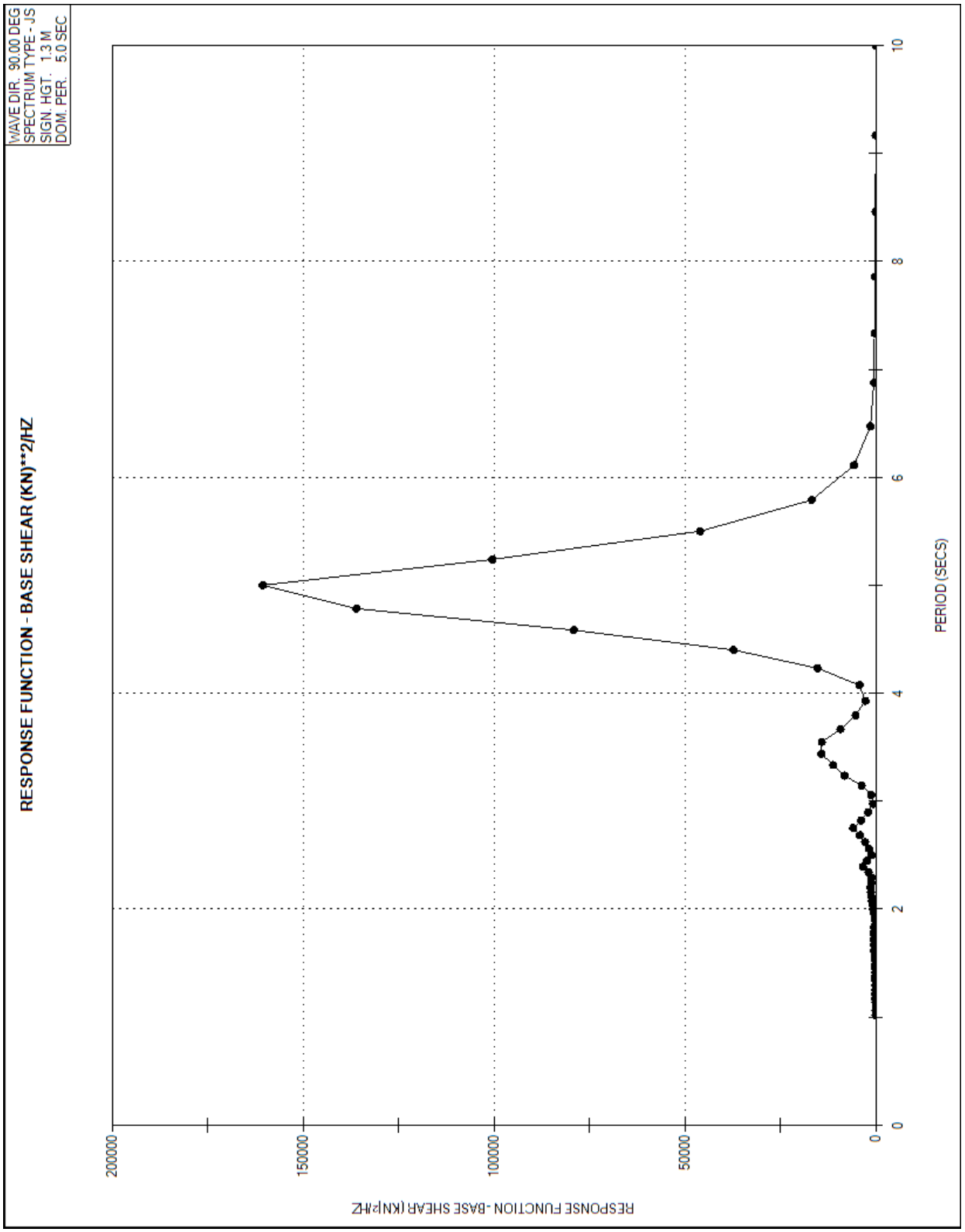

Figure 3-64 Response function (90°, 1/25)

3.7 Dynamic Analysis

For dynamically sensitive systems a dynamic analysis is required to assess the structural response. Such an analysis is required if the natural periods of the structure are in the range where there is sufficient wave energy to excite significant dynamic response. The natural periods of a structure are the most important indicators of the dynamic characteristics of the structure and depend on the stiffness distribution or mass distribution of the model.

The mass that will be dynamically excited and the distribution of that mass should be accurately represented in the dynamic analysis model. For fatigue analyses it is generally appropriate to consider a lower response level and a correspondingly stiffer foundation. Quasi static response analysis is performed using the dynamic analysis model with the mass and damping terms set to zero.

Since the dynamic module in SACS uses the linear theory (i.e. modal superposition), linearized foundation super elements are automatically created at each pile-head by the PSI program. To linearize the foundation for evaluation of fatigue damage, pile stubs of appropriate stiffness are modelled.

An equivalent solution to pile–soil interaction is considered using the pile stub to account for finite deflections of the pile (the P-δ effect). For derivation of the pile stubs, the most probable maximum wave corresponding to the centre of fatigue damage scatter diagram is considered.

A normal in-place analysis with these waves is carried out to obtain the pile head forces. Using these forces, pile stub properties are determined by using "*SINGLE PILE*" module of SACS. Different load cases are used to calculate stiffness in each orthogonal direction as well as the diagonal direction.

With the spectral analysis method, dynamic response can be included by using a frequency domain dynamic solution instead of a quasi-static solution, for the structural analyses used to determine member nominal stresses. The steady state dynamic response to each of the regular waves stepped through the structure is thus included in the resulting hot spot stress range transfer functions.

The linearized (Airy) wave theory is adopted to model the wave elevation, water particle velocity and accelerations. However, this modelling is limited by the linearity of wave component superposition assumptions and does not include nonlinear wave characteristics. Since the fatigue damage accumulation experienced by jackets is mainly caused by wave

loadings due to small and medium sized waves, this linear assumption can normally yield sufficiently accurate wave loading calculation results (Jia, 2008).

Dynamic characteristics (mode shapes and frequencies) of the structure are generated with a reduced structural stiffness matrix and consistent mass approach. When dealing with very large structures (particularly lattice structures) the technique of *mass condensation* may be used (Guyan, 1965).

A set of master (retained) degrees of freedom are selected at each horizontal elevation on the main legs to extract the eigenvalues (periods) and eigenvectors (mode shapes), which includes all stiffness and mass properties related to the reduced degrees of freedom. After the modes are extracted using the master degrees of freedom, they are expanded to include the full 6 degrees of freedom for all joints in the structure.

A consistent mass approach is considered since it is more desirable for structures immersed in the fluid. The added mass is generated automatically by SACS and depends on the size, orientation and proximity of the member to the free surface. Entrapped mass is calculated for members designated as flooded in the model file. Refer to the weight and centre of gravity summary in Table 3-34. Hydrodynamic effects of marine growth are included in the program to account for the density and effective diameter due to marine growth.

For dynamic analyses, energy dissipation due to damping should be accounted for. The choice of damping value can have a profound effect. Offshore structures are very lightly damped. The physical sources of damping are difficult to determine and to quantify with any certainty. For the purpose of a fatigue analysis, damping shall be modelled by a viscous damping coefficient that accounts for all sources of damping including structural, foundation and hydrodynamic effects. For typical pile founded tubular space frame substructures, a total damping value of 2% of critical damping is appropriate.

A relative velocity formulation of the Morison equation inseparably links wave load excitation and hydrodynamic drag damping. It will reduce wave loading experienced and cause implicit additional hydrodynamic damping from drag forces. For small structural displacements, as are typical in fatigue loading conditions, this additional damping is not observed in measurements. Consequently, the relative velocity formulation should not be normally used in the fatigue analysis.

Where required, damping can normally be modelled by viscous damping using a damping ratio (a non-dimensional damping coefficient). Energy dissipation due to damping has a

profound effect on structural response calculations at and in the immediate vicinity of the resonant frequency or frequencies. Outside the resonance region, the influence of damping is negligible.

The eigenvalue parameters for the first 10 mode shapes are presented in Table 3-35. The maximum deflection for modes are presented in Table 3-36 and normalized degrees of freedom are highlighted in the same table. The mass participation factor for retained degrees of freedom (DoF) and expanded DoF are `presented in Table 3-37 and Table 3-38 from the dynamic analysis results. The mass participation factor should be above 90% in at least two lateral directions.

Table 3-34 Weight and centre of gravity summary

********** ITEM DESCRIPTION **********	WEIGHT **********			******** CENTER OF GRAVITY		
	X	Y	Z	X	Y	Z
	KN	KN	KN	M	M	M
PLATE ELEMENTS	2669.964	2669.964	2669.964	0.255	0.628	23.625
MEMBER ELEMENTS	23877.665	23877.665	23877.665	0.864	0.585	4.177
MEMBER ELEMENT NORMAL ADDED MASS	6802.370	6501.305	3587.666	0.344	1.844	-22.250
FLOODED MEMBER ELEMENT ENTRAPPED FLUID	2875.177	2875.177	2875.177	-0.559	2.369	-19.210
LOAD CASES CONVERTED TO WEIGHTS	44923.086	44923.086	44923.086	-0.033	0.784	23.879
********** TOTAL **********	81148.262	80847.196	77933.558	0.254	0.862	14.121

Table 3-35 Frequencies and generalized mass

MODE	FREQ. (CPS)	GEN. MASS	EIGENVALUE	PERIOD (SECS)
1	0.297	5.78E+03	2.88E-01	3.37
2	0.526	4.99E+03	9.17E-02	1.90
3	0.728	3.81E+03	4.78E-02	1.37
4	1.479	1.26E+02	1.16E-02	0.68
5	1.547	4.55E+02	1.06E-02	0.65
6	1.645	2.61E+03	9.36E-03	0.61
7	2.037	2.58E+03	6.10E-03	0.49
8	2.434	8.12E+03	4.28E-03	0.41
9	2.658	3.43E+03	3.59E-03	0.38
10	2.690	5.61E+03	3.50E-03	0.37

Table 3-36 Maximum deflection for modes

Mode	X-Defl. cm	Joint	Y-Defl. cm	Joint	Z-Defl. cm	Joint
1	-0.017	7520	**2.540**	**7120**	0.076	7110
2	**2.540**	**7520**	0.050	6101	-0.115	199
3	**2.540**	**7120**	-1.222	7501	0.072	101
4	0.013	181	**2.540**	**104**	-0.007	381
5	-0.027	399	**2.540**	**111**	-0.027	199
6	**2.540**	**281**	0.333	103	0.523	6120
7	**2.540**	**201**	-1.888	201	-0.407	301
8	-1.909	219	**2.540**	**7120**	1.818	6120
9	1.557	219	**2.540**	**115**	-1.877	7520
10	1.997	201	1.848	112	**2.540**	**7101**

Table 3-37 Mass participation factor based on retained DoF

Mode	X	Y	Z	Cumulative		
1	0.0000003	0.8306850	0.0000029	0.000000	0.830685	0.000003
2	0.8809174	0.0000001	0.0000022	0.880918	0.830685	0.000005
3	0.0001817	0.0000461	0.0000009	0.881099	0.830731	0.000006
4	0.0000383	0.0103685	0.0004366	0.881138	0.841100	0.000443
5	0.0000165	0.1512184	0.0000080	0.881154	0.992318	0.000451
6	0.0980083	0.0000015	0.0002527	0.979162	0.992320	0.000703
7	0.0001535	0.0000058	0.0000221	0.979316	0.992326	0.000726
8	0.0047990	0.0004347	0.0005199	0.984115	0.992760	0.001245
9	0.0052279	0.0001086	0.4845560	0.989343	0.992869	0.485801
10	0.0041544	0.0000377	0.4666680	0.993497	0.992907	0.952469

Table 3-38 Mass participation factor based on expanded DoF

Mode	X	Y	Z	Cumulative		
1	0.0000003	0.8400767	0.0000029	0.000000	0.840077	0.000003
2	0.8886507	0.0000001	0.0000022	0.888651	0.840077	0.000005
3	0.0001883	0.0000478	0.0000009	0.888839	0.840125	0.000006
4	0.0000365	0.0099481	0.0003967	0.888876	0.850073	0.000403
5	0.0000157	0.1427269	0.0000067	0.888891	0.992800	0.000409
6	0.0933678	0.0000012	0.0002533	0.982259	0.992801	0.000663
7	0.0001411	0.0000038	0.0000219	0.982400	0.992805	0.000685
8	0.0042038	0.0004773	0.0005203	0.986604	0.993282	0.001205
9	0.0044583	0.0001119	0.4847427	0.991063	0.993394	0.485948
10	0.0035019	0.0000491	0.4667915	0.994564	0.993443	0.952739

*** EFFECTIVE WEIGHT: X 81038.307 KN, Y 80728.788 KN, Z 77836.332 KN

Mode shapes for the first 10 mode of vibrations are presented in Figure 3-65 to Figure 3-74.

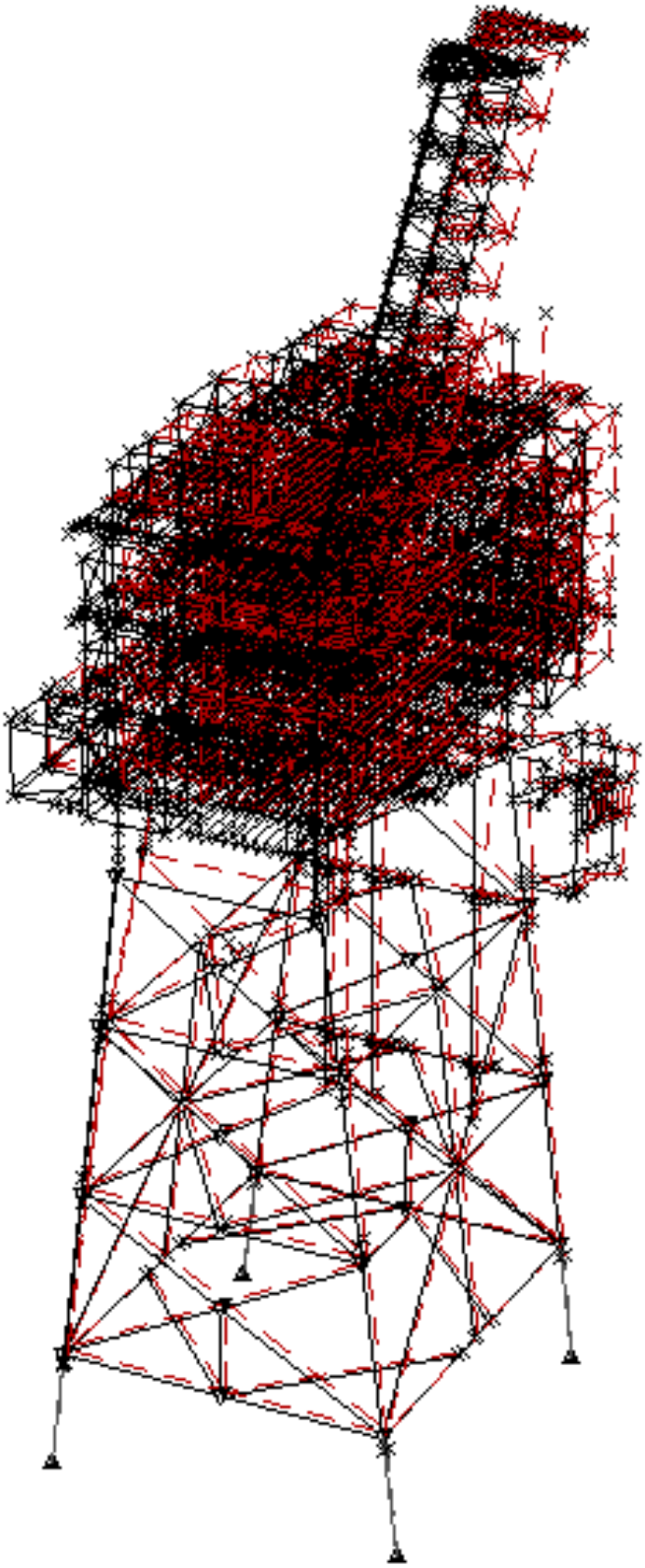

Figure 3-65 Deflected mode shape 1

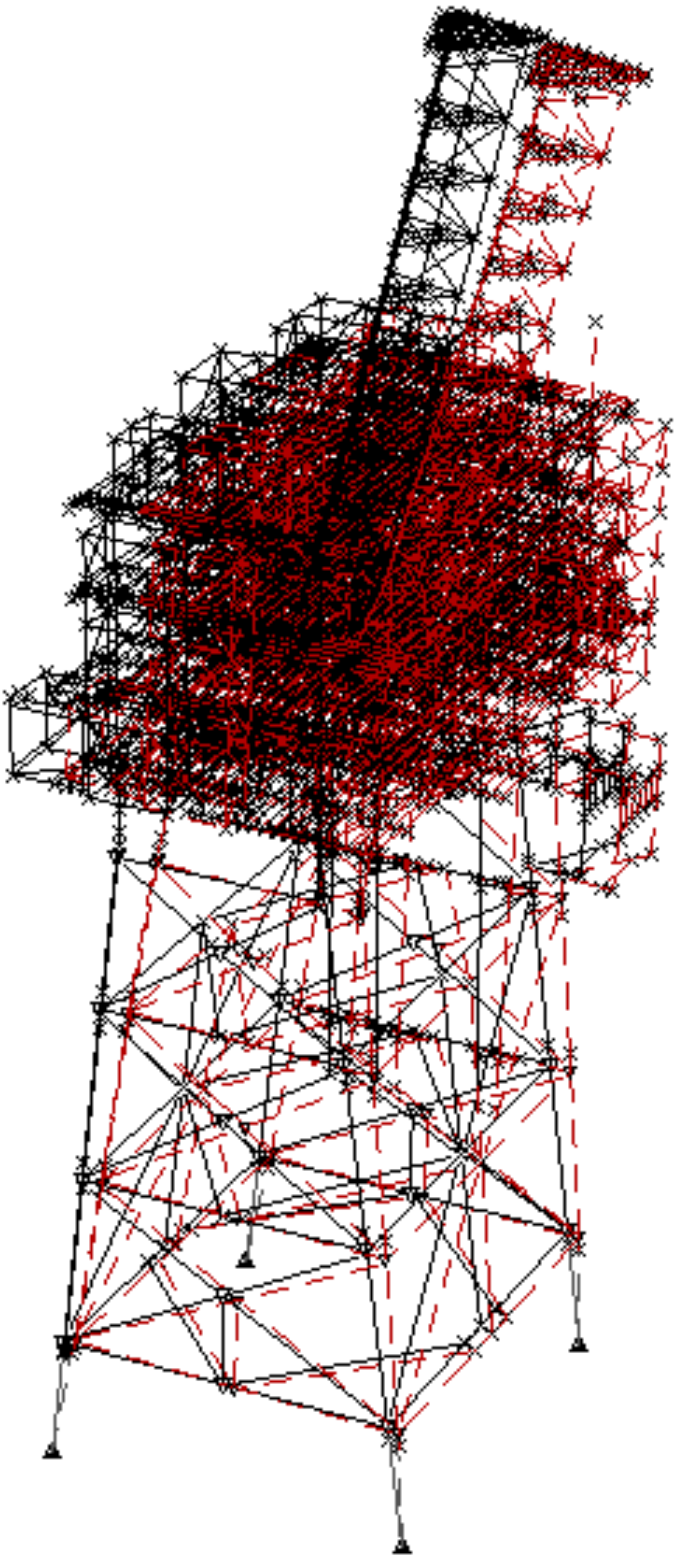

Figure 3-66 Deflected mode shape 2

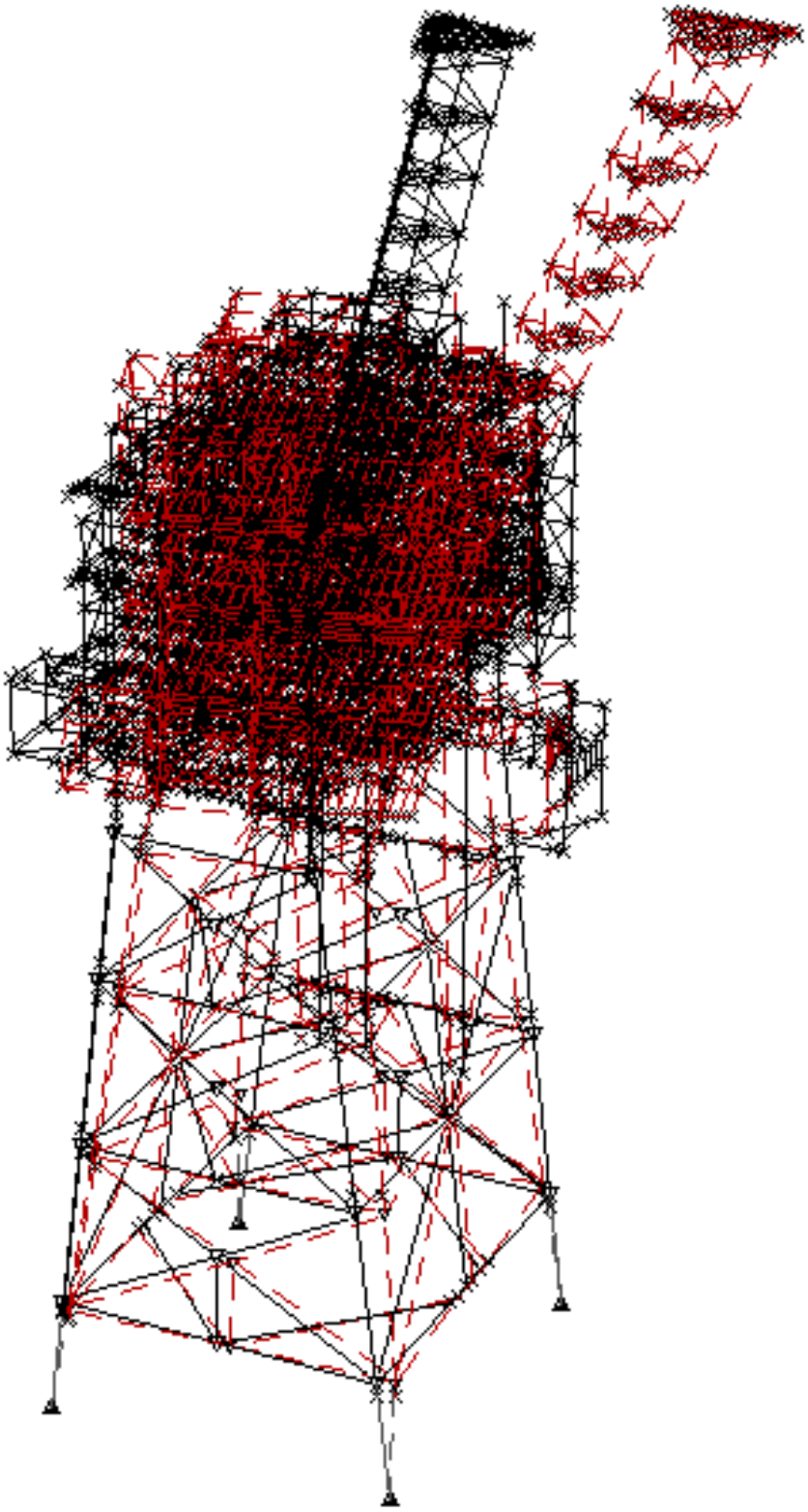

Figure 3-67 Deflected mode shape 3

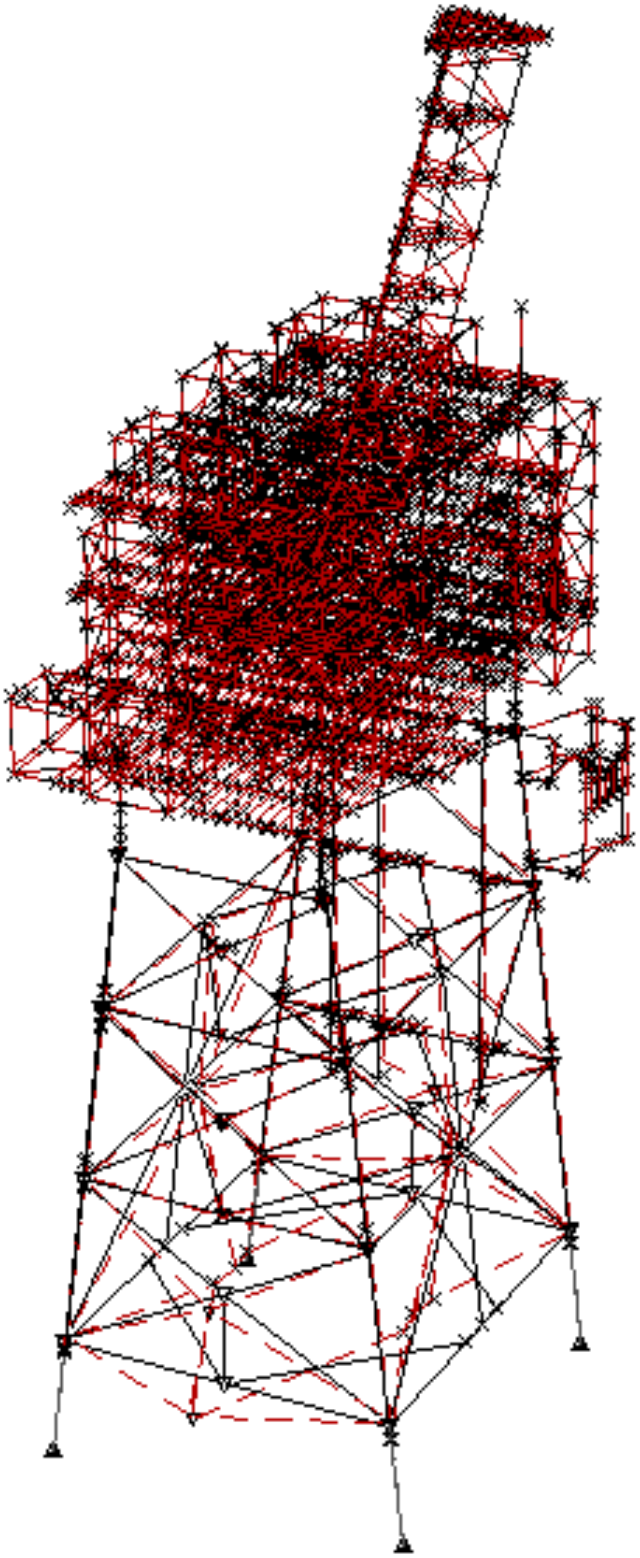

Figure 3-68 Deflected mode shape 4

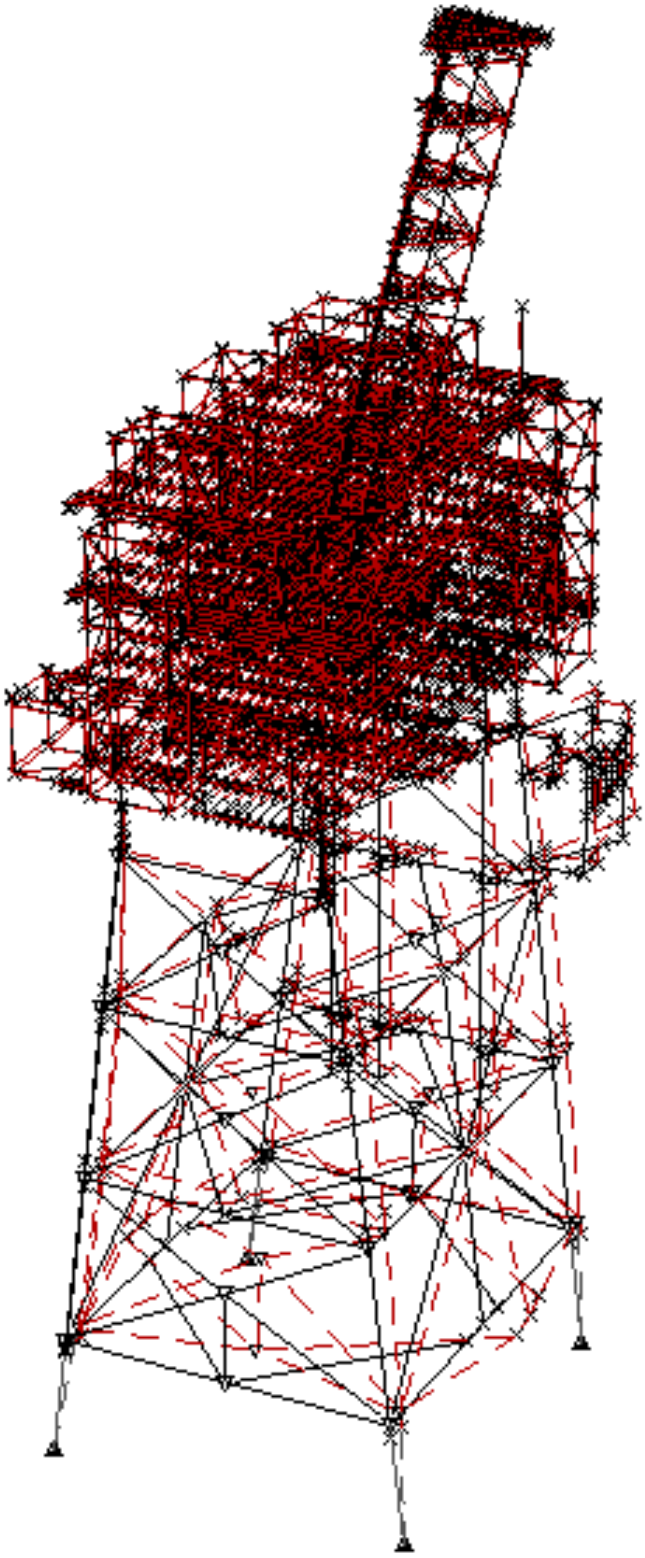

Figure 3-69 Deflected mode shape 5

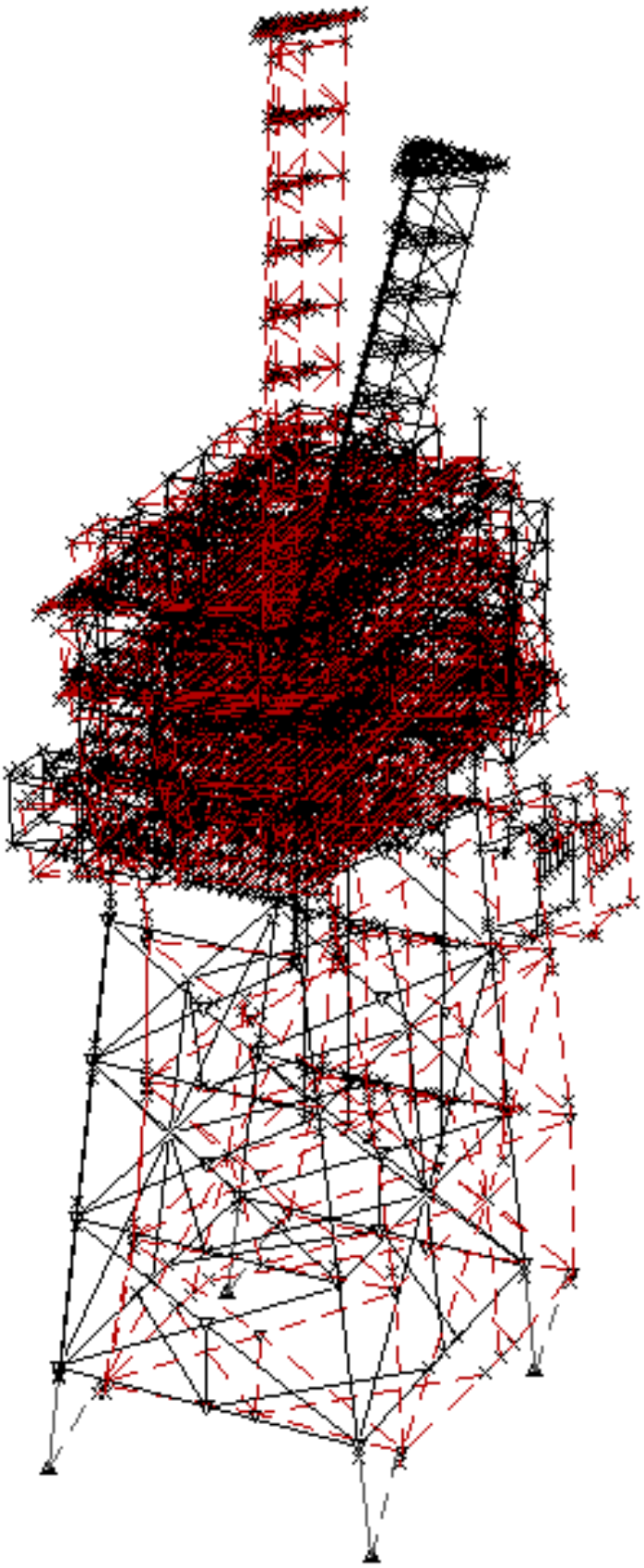

Figure 3-70 Deflected mode shape 6

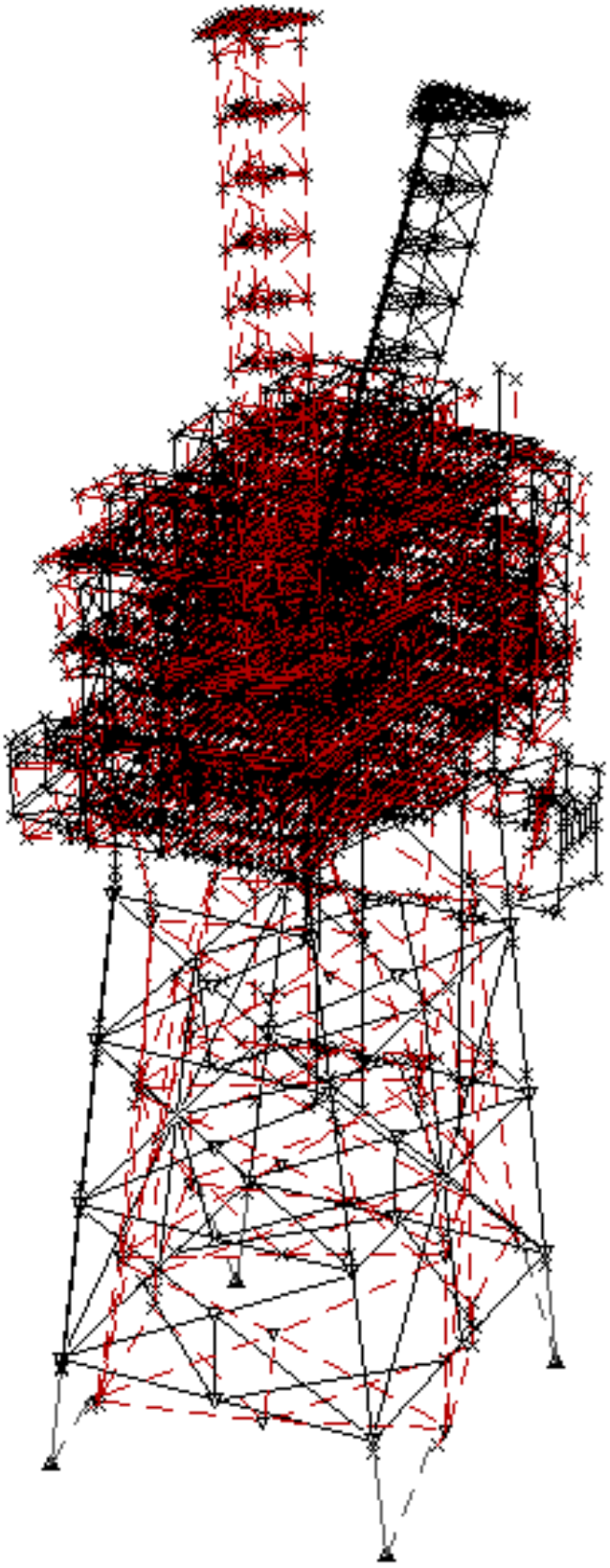

Figure 3-71 Deflected mode shape 7

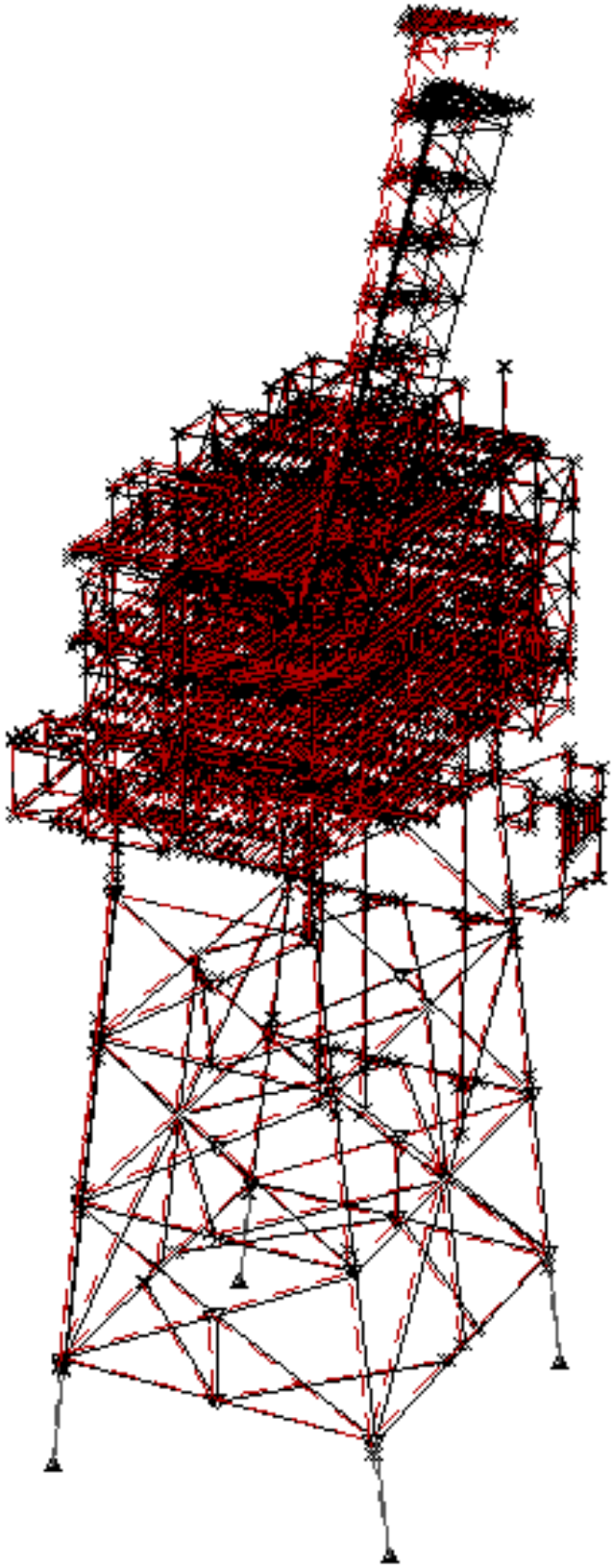

Figure 3-72 Deflected mode shape 8

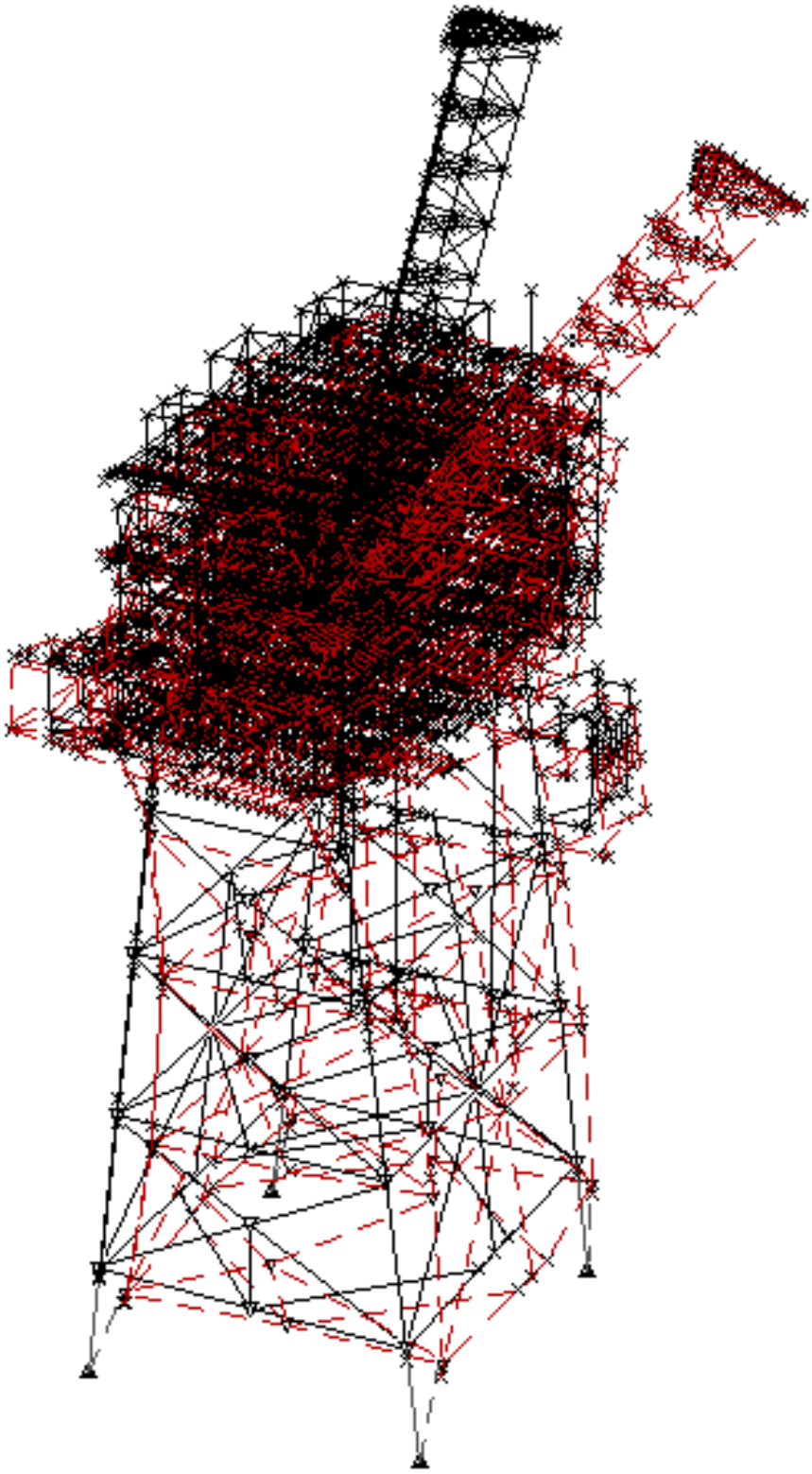

Figure 3-73 Deflected mode shape 9

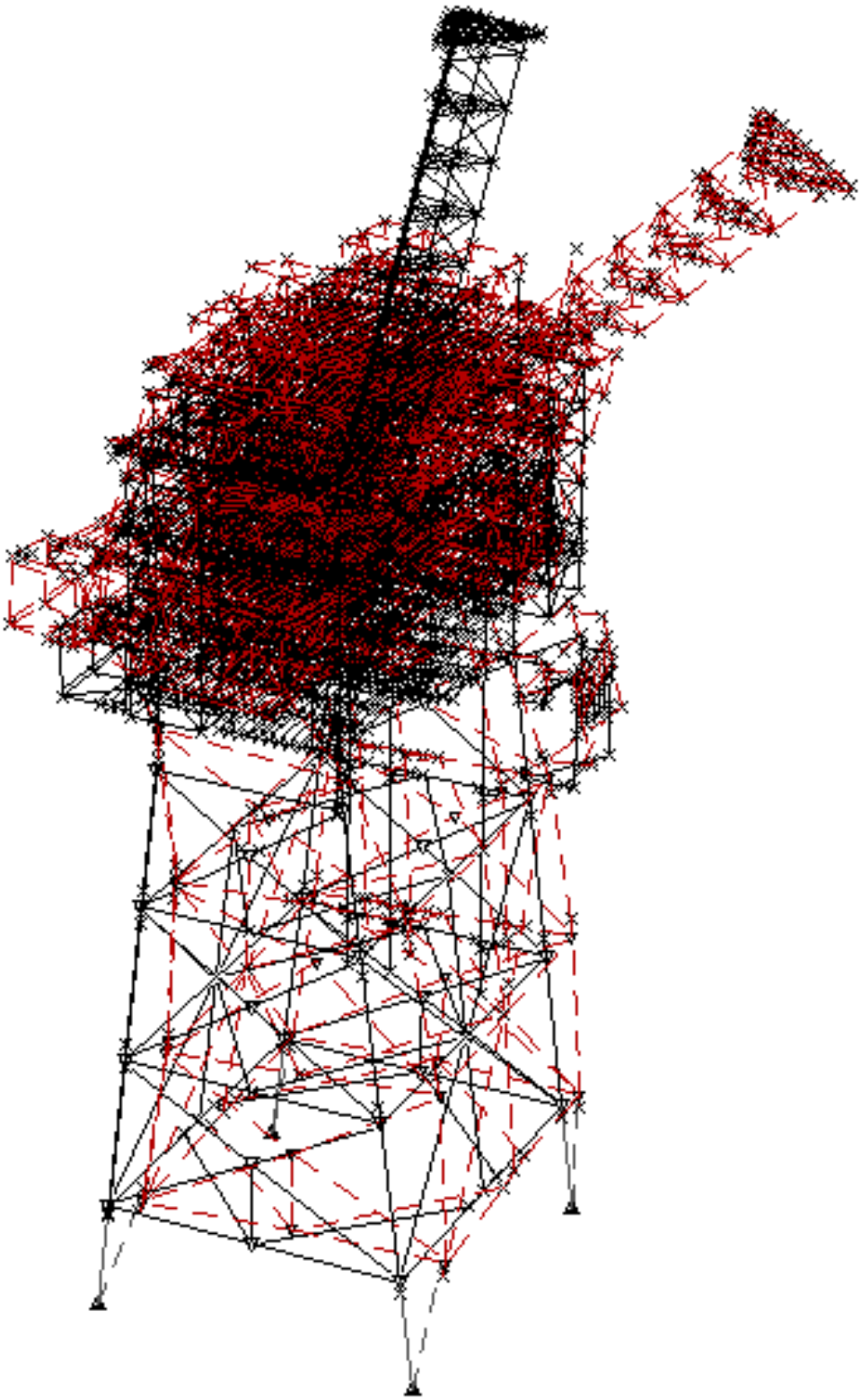

Figure 3-74 Deflected mode shape 10

Chapter 4 Discussion

Modern offshore petroleum industry has been developed since 1947 at a fast pace through its significant milestones that have created a whole new phase of findings and producing crude oil and natural gas. The literature on fixed offshore structures is investigated to identify the significance of the procedure adopted for the study and its outcome.

The empirical techniques are calibrated against more advanced analysis techniques to take account of actual physical response process in a conservative manner. The outcome of adopted procedure is discussed in detail with a case study of parameters involved in design. A good balance is achieved between complexity and accuracy in the applied process.

4.1 Outline of the procedure

Studies on nonlinear environmental conditions and subsequent structural behaviour is discussed in detail. Nonlinear structural behaviour is studied using methods based on equivalent linearization and frequency domain expansions using transfer functions. Some of the data of the survey are attached in Appendix A.

A simplifying assumption was to neglect the effects of the relative movement of the structure with respect to the water velocities to linearize the structural behaviour. Otherwise this nonlinearity raises difficulties in solving the problem in the frequency domain and is restrictive to the procedure adopted. A further restraint is the application of Miner's rule which is assumed to be deterministic. However, the method has been developed to take account of randomness in the response process.

Dynamic effects of sea waves and their importance in fatigue degradation are discussed in the literature review. Further to that it is discussed how to incorporate these effects in the analysis in Sections 3.5 and 3.6. It is suggested to perform sensitivity analyses to obtain a clear representation of the structural dynamic behaviour. This can be performed by varying the key parameters, which are subject to change, e.g. the operating weight of the platform, the foundation stiffness and the structure's natural period.

The dynamic amplification effects could be severely suppressed if the natural period falls on the wave load cancelation point. Conversely with only a small shift in period a huge dynamic amplification is expected. Therefore, sensitivity analysis is important to verify the accuracy of the method as a practical and robust assessment tool. Dynamic response analysis methods are based on the matrix equilibrium equation (Equation 4-1).

$$M\ddot{r} + C\dot{r} + Kr = F(t)$$ Equation 4-1

Where;

M = mass

C = damping

K = stiffness matrix

r = nodal displacement vector

$F(t)$ = nodal load vector (includes relative velocities)

In the above equation dot superscript designates differentiation notation for time derivative. The right hand side of the Equation 4-1 (the force vector) contains all the possible nonlinear effects, like drag damping and free-surface variation, which means that the dynamic model can be simplified by linearization of the force vector with a proper linearization procedure taking account of linearization point.

Simplified methods are more applicable to fatigue environmental conditions compared to extreme environmental conditions. However, this practice will require a good awareness of dynamic response interaction with dynamic characteristics of the structure and excitation forces to properly reflect all dynamic effects in simplified methods.

For instance the dynamic transfer function in Figure 3-32 reveals considerable amplitudes particularly around the resonant frequency. This incident could be expected when excitation frequencies coincide with the natural frequency (Leira, 1990).

In the same figure cancellation/enhancement effects of hydrodynamic forces is observed as troughs/peaks of the transfer function curve at frequencies where the distance between the foremost and backmost leg is equal to a multiple of a half/full wavelength respectively.

A realistic dynamic response is expected with a reliable representation of the frequency content in the wave condition. The variation of design parameters like operating weight and water depth of the structure changes the amplitude and frequency content of the resulting time history. Therefore, a sensitivity analysis should be carried out to study the effect of water depth and operational weight on the model transfer function.

The concern of the present study is to investigate an analytical solution of the fatigue assessment through a statistical analysis that suits a random process. For this purpose the stress range PDF (Probability Density Function) is obtained directly from a power spectrum to predict fatigue damage. The other alternative is the application of Rain flow cycle counting to

obtain stress range histograms from time consuming measurements. Therefore, using the power spectrum of the associated stress time series is preferred to extensive simulation in the time domain method.

For stationary excitation, fatigue damage can be predicted with a minimum amount of data from the resulting stress range PDF with confidence, which makes the spectral method a desirable solution. Such stationary situations are limited in duration and the wave environment will not remain stationary for longer terms. As the result, the stress cycles for the random process may not be realized in the stationary situation (short term condition). Therefore, the description of the wave environment should be representative of the long term conditions.

The situation will not remain stationary nor Gaussian for long term wave climates. Consequently, relative phasing of periodic components becomes important in fatigue estimation. Considering that in the spectral method no phase information is retained in a power spectrum, this will make the response PDF more complex. Although there is no conventional method to obtain the response PDF for broad band processes, a system's response may approximate to Gaussian if its narrow band response derived from a broad band excitation. However, an assumed Gaussian PDF should be treated with uncertainty at the tails of the distribution.

For narrow band Gaussian processes, the PDF of the peaks and the resultant stress ranges are assumed with Rayleigh distributions, which means that the behaviour of the fatigue damage is only dependent on the current stress states as the case for the non-ageing effect process. Therefore, statistical modelling under random loading is simplified and fatigue damage can be obtained by the stress range and the number of cycles based on the Miner's rule. This implies that the load sequence interaction is negligible so that the total damage is the linear summation of the fractional damages caused by individual stress ranges.

The realistic distribution of wave energy over the relevant frequency range can be suitably accounted for using spectral analysis. Transfer functions are the corner stones of the spectral approach, which incorporates the dynamic characteristics of the structure. An appropriate frequency grid is selected with reliable interpolation routines to ensure a good definition of peaks and valleys in the global base shear transfer functions, refer to Figure 3-32. The frequency intervals obtained must be small enough for precise calculation of spectral moments.

The spectral moments are obtained from integrations of response spectra base on the frequency considered for integration points and wave direction in the case of multidirectional sea

spectrum. The locations of integration points are very important to avoid ambiguous integration results (Karadeniz, 2008). Furthermore, the termination of the calculation at the tail of the frequency range should be considered with care to prevent numerical errors due to ignoring a significant portion of the response.

Considering the above, the global base shear transfer functions are developed for the wave steepness related to the weighted centre of damage in the scatter diagram. The weighing factor is the mean value of the normalized static base shear transfer function over the width of each cell in the scatter diagram. This weighing factor introduces a stress period dependency, which allows the cancellation effects to be reflected in the fatigue damage scatter diagram.

Determination of wave height is obtained by a calibration process. Calibration of the wave steepness should be based on the matching of global response parameters, which are representative of the predominant wave action to which the structure is subjected to under fatigue conditions. The appropriate wave steepness is calibrated so that the spectral maximum base shear wave load range matches the deterministic value. Calibration is performed for a broadside, an end on and a diagonal wave direction.

Use of constant wave steepness gives unrealistically large wave heights at low wave frequencies (large wave lengths). Therefore, wave height at the low frequency side is capped to the wave height with a one year return period as a maximum. Moreover, if the dynamic amplification of the structural response is significant, special attention must be given to the high frequency cut off point.

It has been shown that for a more general narrow band spectrum, Figure 3-30 (a), the high frequency components introduce irregularities in the sine wave form approximation as additional maxima. Accordingly, a minimum wave height of 0.3 m is considered to avoid these irregularities.

The wave environment is characterized by the annual variability of the sea surface and directional spreading. The width of the spectral density and the directional spreading affect the nonlinear characteristics of the waves. Although wave directionality and energy spreading generally reduce the structural response, their effects in shallow water may be different than that of deep water situations (Prevosto, 1998).

The influence of wave directional spreading on the stress variations is investigated in a case study, which is of some significance (refer to Appendix B). In most cases the influence of wave directional spreading is of secondary importance and can be neglected. However, this

effect can be considered by choosing an appropriate wave spreading function if it is prominent (ISO19902, 2007). The results from case studies show that the fatigue life is increased in most of the joints using a cosine spreading function.

The space frame model for fatigue analysis includes all important characteristics of the stiffness and loading properties of the piled structure. The model stiffness includes the three dimensional distribution of platform stiffness (Figure 1-1). Offsets are specified for jacket tubular members so that braces are modelled to the face of the chord and a 5 cm gap (at the chord face) exists between braces. Member end stresses are then calculated at the face of the chord.

Member offsets are used to shorten or lengthen the member or to move the member when the neutral axis is not located on the line between its connecting joints. When offsets are specified, the program creates a rigid link between the neutral axis of the member end and the connecting joint. The offsets describe the length of the rigid link and should be used considering chord shell flexibility.

Structural components are considered in sufficient detail for fatigue analysis considering beam and finite elements (e.g. shear plates). The stiffness of appurtenances can be ignored unless it significantly changes the global stiffness of the structure. Deck plate is considered in sufficient detail using shear plates for coarse finite element mesh representation. Topside deck should be modelled in the detail in terms of topside stiffness, total topsides mass, centre of mass and the rotational inertia of the deck mass to present a realistic deck-jacket interface and precise torsional response. The equivalent linear foundation model (super element) is used due to requirement of linear theory (i.e. modal superposition) in dynamic analysis.

The super element is created for low deflection levels to represent the foundation stiffness for fatigue environment. Since the pile load-deflection curve is nonlinear, soil springs representing pile stiffness vary for different load levels. In mild environmental condition as is the case for fatigue waves spring stiffness is much greater than the spring stiffness appropriate for extreme wave loads (Kinra, 1979). Therefore, spring stiffness associated with extreme environmental conditions is not applicable for fatigue assessment.

The inertia effects of the structure substantially contribute to fatigue damage. The dynamic inertia force on a structure is due to its vibrations and calculated using a spectral technique and then scaled to match the global base shear response obtained from a Rayleigh distribution. There is uncertainty involved in the global response due to variation in the mass, damping and stiffness properties, which affects the calibration process. Therefore, the natural period of the

platform could be carefully mapped not to fall in a valley of the platform base shear transfer function. In other words, the period is to be shifted to the adjacent peak of the transfer function by attuning mass or stiffness within expected range, refer to Figure 3-39. Furthermore, sensitivity analysis may be carried out by varying the foundation stiffness. This will affect the member loads, especially near the mud line, which is prone to fatigue damage.

The mass model in dynamic analysis includes the topside and substructure weight, marine growth, entrapped water and added mass. A lumped mass model can be used for global structural response but it does not capture the local dynamic effects. Distribution of mass along the element can be considered by a consistent mass approach in which case the mass matrix created incorporates off-diagonal coupling terms between all degrees of freedom, including rotational DOFs. Since in the lumped mass approach off diagonal terms are assumed to be zero, it is not recommended when the element mass is not the same in all three directions. This could be the case when including effects of fluid added mass or virtual mass acting normal to the element. Considering the above, a consistent mass model is considered in the analysis.

Energy dissipation due to damping has a profound effect on the structural response at a resonant frequency. Instead of precise modelling, all sources of damping including structural, foundation and hydrodynamic effects are accounted for by considering an equivalent viscous damping that is 2% of critical damping. Damping modes in an offshore structure are hysteretic and friction damping; however, it is mathematically more convenient to obtain the correct energy loss per cycle by viscous damping. The relative velocity formulation is not used in the fatigue analysis since it will cause additional damping that is not observed in measurements (ISO19902, 2007).

In fatigue analysis the wave theory as well as drag and mass coefficients considered are different from those used in strength analyses for design wave loads (refer to 2.4). Furthermore, the current static effect can be neglected since we are dealing with the stress range. At the same time, current dynamic effect is complicated to account for in fatigue analysis. Although the analysis technology is lacking to incorporate these effects, it can only affect platform dynamics for large waves or currents, which is not the case for mild environments.

The effect of marine growth on the hydrodynamic actions is considered by increasing the cross-sectional dimensions of structural components at the marine growth zone as member drag diameter. Tubular structural members in this zone are classified as rough where the drag and inertia coefficient of rough members is considered in Morison’s equation (API, 2007).

Marine growth weight is included in the mass model, which increases the platform added mass. The local and global wave loading will increase due to marine growth effects and cause further fatigue damage of members subjected to these additional loads.

Stress concentration factors consistent with corresponding S-N curve are utilized to evaluate local scale stresses. The fatigue life of the platform is evaluated using Miner cumulative damage summation on each sea state. The short term stress distribution is assessed using spectral methods assuming a narrow banded Rayleigh distribution in closed form for each sea state.

A calibration procedure is employed to compensate the uncertainties involved in wave action and resulting stress, which is discussed in more details in Section 3.6. Safety factors on the fatigue life are considered based on the component's criticality and in-service inspection requirements (API, 2007). Stress concentration factors are used for extrapolation of stresses to the weld toes. The S-N curve includes the local weld toe effects, such as notch stresses. Hot spot stress ranges are evaluated at eight locations termed saddle and crown (refer to Figure 4-1) around each tubular chord-brace intersection.

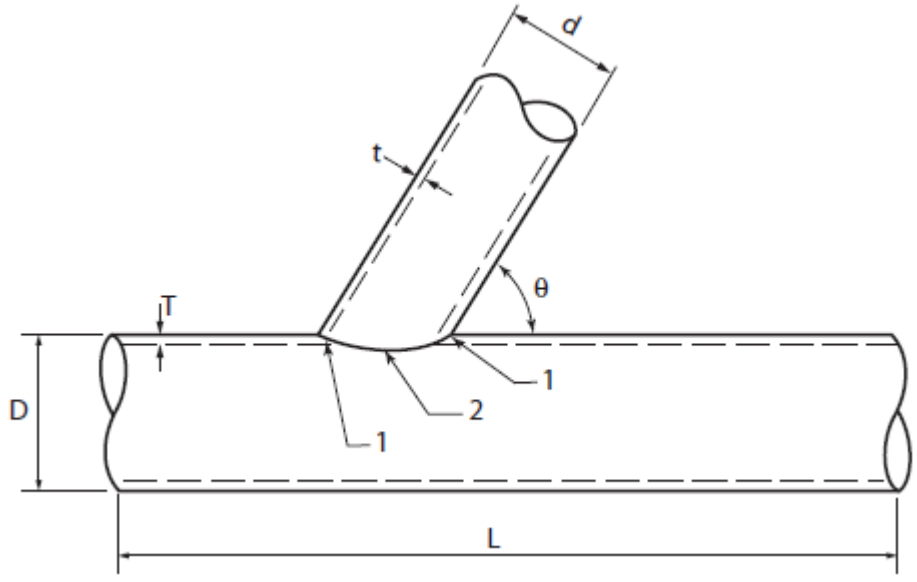

Figure 4-1 Tubular intersection (1 crown, 2 saddle)

Stress Concentration Factor (SCF) by Efthymiou is utilized, which is based on finite element analysis including all joint and load types. Miner summation law is adopted to predict fatigue life due to variable actions based on the following assumptions:

- A relation between stress range and the number of cycles to fail the material (S-N curve) can be found based on sinusoidal varying stresses.
- The same S-N curve can be used for varying stresses that are not sinusoidal where the difference between the maximum and minimum stresses in a cycle is taken as the stress range.
- An amount of damage for a material subjected to a stress range, s, for a number of cycles, n(s), smaller than the number of cycles to failure is given by Equation 4-2

$$d = \frac{n(s)}{N(s)} \qquad \text{Equation 4-2}$$

- A material subjected to different stress ranges will fail when the sum of damages for each stress range equals unity, that is:

$$\sum d_i = \sum \frac{n(s_i)}{N(s_i)} = 1.0 \qquad \text{Equation 4-3}$$

Within the framework of the Miner theory the fatigue analysis is performed using the spectral (statistical) approach to yield more realistic and reliable results than the deterministic analysis.

4.2 Results

Wave induced dynamic force is the main contributor to fatigue damage of offshore platforms. It exposes lateral loads on the structure that cause member severance and consequent reduction in structural integrity. The fatigue inducing loads could excite dynamic response followed by intensified fatigue stresses in the structure since they are variable with time.

The dynamic effects and structural response to excitation forces are adequately modelled to study fatigue performance with realistic results. The results from different methods are compared to highlight the applicability of the analysis method to dynamically responding structures under random nonlinear wave loading.

As per the central limit theorem a random process may have a Gaussian probability distribution if it results from the summation of infinitely random elementary events. The effective bandwidth of the random process can be reduced using selective filters so that a time domain formulation can be transformed to frequency domain.

Only time varying loads are considered for the action model using the spectral method in the frequency domain. This method retains the random nature and frequency content of the random sea and is regarded as the most reliable method for fatigue assessment. The assessment delivers a usage factor representing the amount of fatigue damage using Miners rule of cumulative damage.

The purpose of the Dynpac program module is to generate dynamic characteristics (mode shapes and frequencies) of a structure. Modal analysis is performed to identify the structural characteristics that contribute to the dynamic response. For this purpose, a Guyan reduction is performed to reduce the structural stiffness matrix as well as the mass matrix. The eigenvalues are initially extracted for the master degrees of freedom and then expanded to reduced (slave) degrees of freedom, which will then be used in the calculation of the modal reactions.

The dynamic characteristics are considered in wave response analysis while generating the equivalent static loads. This includes hydrodynamic loading determined by Morison's equation as well as inertia loading determined from modal acceleration. An equivalent static load case is solved to obtain the nominal stresses. Nominal stresses from solution results are employed to create the transfer functions required for the spectral fatigue analysis.

The methods based on stochastic linearization are investigated using constant wave steepness. The empirical techniques are calibrated against more refined random analysis techniques using global response parameters to take account of actual physical response processes in a conservative manner. A calibration procedure is conducted by adjusting the wave steepness and parameters in Morison equation to obtain comparable results with conventionally calculated force levels. A good balance is achieved between complexity and accuracy in the applied process.

The spectral fatigue assessment is referred to as the direct method because it produces results in terms of fatigue damage. This method used is based on transfer functions, which require a linear relationship between wave height and wave induced loads. However, adjustments are made to the basic method to account for various nonlinearity. Transfer functions are obtained from a deterministic calculation and considered as the corner stone of probabilistic fatigue analysis.

Fatigue assessment is conducted with the aim for more economical design and reduced inspection without compromising the structural safety levels. Fatigue results are very sensitive to stress distribution due to an exponential relationship between the stress range and the allowable number of cycles; therefore, stress histories are precisely evaluated considering a

Rayleigh distribution of peak stresses, which yields accurate results (even for structures with significant nonlinearities) as compared to a Weibull fit of the peak distribution.

The nominal stresses are obtained from the global analysis based on the wave frequency and approach direction using linear (Airy) wave theory. The effect of nonlinear wave action is approximated by a suitable wave height selection. The computer model includes both the structural model and the action model for stress analysis. The structural model is adequately detailed in terms of geometry, stiffness, damping and mass distribution for precise evaluation of the torsional response. Static loads are included only for the determination of the equivalent pile stub. For stiffness modelling half of the corrosion allowance is considered for the average thickness during the life of the structure.

In low to moderate seas, which is applicable to the fatigue environment, a confused short crested sea condition is expected. Therefore, some case studies are carried out to examine short crested sea condition in fatigue assessment by applying the wave spreading functions, which modify the spectral moment. However, consistent relationship between the results may not exists due to the nonlinear nature of the wave environment.

Stress raisers from the global geometry of the connection are accounted for in stress concentration factors, which is referred to as the geometric hot spot stress. In fatigue analysis, stress concentration factors (SCF) are determined using load distribution through the connection. Analysis results are presented in tabulated forms in Table 4-1 for 8 different case studies. Extended detail results for the calibrated case is included in the Appendix B. A graphic display of the selected joint numbers is presented in Figure 4-2. Fatigue life comparison to the calibrated case is presented in Table 4-2. The interpretation of the results for case studies and their assumptions are discussed further in Section 5.1.

Table 4-1 Fatigue life of selected joints for different case studies

case / Joint	C1	C2	C3	C4	C5	C6	C7	C8
101	3798	54084	38688	7883	26054	8091	3738	3798
201	9775	95398	60626	21579	64092	21577	9594	9775
301	542	15905	7520	1144	4327	1146	534	542
401	23052	113524	17553	10246	21264	13135	13758	23052
119	3449	91509	37892	6843	25454	7173	3406	3449
219	10309	114065	73969	23056	52002	22941	10142	10309
319	526	15319	7181	1107	4163	1111	519	526
419	28999	150369	24007	13213	28941	17026	17941	28998

Table 4-2 Fatigue life comparison to calibrated case

case / Joint	C1/C1	C2/C1	C3/C1	C4/C1	C5/C1	C6/C1	C7/C1	C8/C1
101	1.00	14.2	10.2	2.1	6.9	2.1	0.98	1.00
201	1.00	9.8	6.2	2.2	6.6	2.2	0.98	1.00
301	1.00	29.3	13.9	2.1	8.0	2.1	0.99	1.00
401	1.00	4.9	0.8	0.4	0.9	0.6	0.60	1.00
119	1.00	26.5	11.0	2.0	7.4	2.1	0.99	1.00
219	1.00	11.1	7.2	2.2	5.0	2.2	0.98	1.00
319	1.00	29.1	13.7	2.1	7.9	2.1	0.99	1.00
419	1.00	5.2	0.8	0.5	1.0	0.6	0.62	1.00

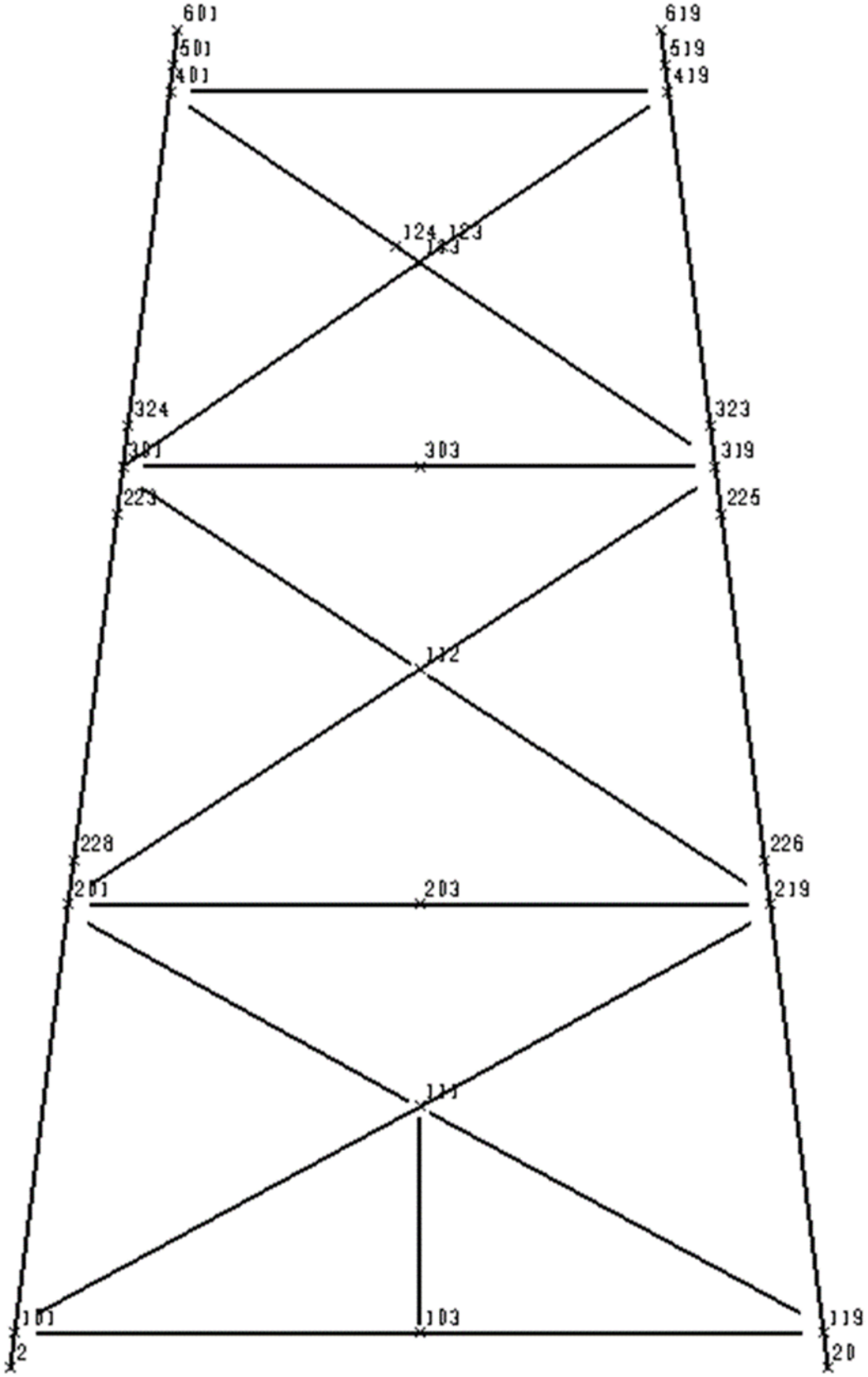

Figure 4-2 Face A joint numbers

Chapter 5 Conclusion

The outcome of the research study has advanced the fatigue assessment procedure of offshore structures. The methodology used here is frequency domain analysis, which accounts for non-linear system responses with due consideration of the system vibration characteristics. In this regard a rigorous calibration process is employed to take account of the actual physical response process in a conservative manner. The applicability of the proposed approach is demonstrated in detail by applying the aforementioned methodology to a fixed jacket type offshore platform in the Persian Gulf.

5.1 Summary

In this thesis, a practical method for dynamic fatigue assessment of fixed offshore platforms is investigated. The literature review is conducted to identify the most appropriate design methods and their significance in meeting functionality, safety and economical aspects. The random nature of the wave environment is represented by frequency domain spectral methods using a suitable linearization in a moderate environment. The accuracy and efficiency of the method is verified by calibration techniques with due consideration of dynamic characteristics.

Fatigue damage is the main cause of structural failure in fixed offshore platforms and reduces overall structural integrity during its development. For platforms with periods greater than 3 seconds (refer to Table 3-35) the effects of dynamic and structural response which are incorporated through a calibration process become more important and must be adequately modelled to ensure that realistic results were obtained. The detailed description of analysis techniques are discussed in Chapter 3.

The response of the system to random excitation is monitored for optimization of its peak performance. In this regard some case studies are developed by varying the key parameters, which are subject to change. The results are tabulated in Table 4-1 and compared in Table 4-2. The assumptions and outcome of the case studies are discussed below.

1. Calibrated spectral dynamic fatigue results (C1)

   The calibration method is discussed in detail in Section 3.6, which delivers the most accurate results for dynamic fatigue assessment of fixed offshore platforms using spectral techniques in frequency domain and a comparison of other case studies are conducted against this case.

2. Fatigue results ignoring calibration (C2)

A graphic display of fatigue life for selected joints is provided in Figure 3-38. For dynamically sensitive platforms, the dynamic effects and random nature of the wave environment are considered using calibrated spectral techniques against conventional techniques. The comparison of the results show that fatigue life ignoring calibration would be unrealistically higher than expected with the rigorous methods used in the research study. This shows the importance of using proper analysis techniques to obtain a realistic result with due consideration of dynamic effects.

3. Wave spreading options

- Wave spreading based on transfer function averaging (cosine distribution power 2, C3)
- Wave spreading based on API energy approach (cosine distribution power 2, C4)
- Wave spreading based on transfer function averaging (cosine distribution power 4, C5)
- Wave spreading based on API energy approach (cosine distribution power 4, C6)

Wave spreading is the basic component of the wave environment, which affects fatigue life estimates. An appropriate spreading function (e.g. cosine squared) may be used in conjunction with the wave spectrum to account for the effect of wave spreading on structural responses. Applying the wave spreading function modifies the spectral moment and reduces the structural response. However, their long term statistics are not yet commonly available and their effects in shallow waters may be different than that of deep water situations.

The influence of wave directional spreading on the stress variations is investigated in 4 case studies as mentioned above, which are of some significance. Cosine distribution power 4 is used when limited fetch restricts the degree of spread. The results from the case studies shows a significant increase in predicted fatigue life in most of the joints. However, there is uncertainty involved on the power in the cosine function. As a conservative recommendation, the most unfavourable condition should be adopted for the design of fixed offshore platforms.

4. Inclusion of crest or trough in Airy wave theory (C7)

The wave kinematics are computed using nonlinear Airy theory by inclusion of crest or trough. It is observed that the influence of nonlinear waves is most prevalent on the joints close to water surface with 40% reduction in fatigue life. However, this assumption is not consistent with linearity demand in spectral analysis; therefore, a direct conclusion cannot be drawn from this observation and a sensitivity study should be carried out to quantify this influence.

5. Unsorted equivalent static loads option saving execution time (C8)

The fatigue results will remain the same when using unsorted equivalent static loads in wave response analysis (US option). However, this method does not generate a modal response factor to save the execution time and recommended for fatigue analysis.

5.2 Recommendation

It is recommended to perform a rigorous calibration technique for fatigue design of fixed jacket type offshore platforms in hostile wave environments. The calibration process is discussed in detail in thesis subject, which has advanced fatigue assessment of offshore structures. This method is using frequency domain tools to account for non-linear system responses with due consideration of the system vibration characteristics. The applicability of the proposed approach is demonstrated in detail by applying the aforementioned methodology to a fixed jacket type offshore platform in the Persian Gulf as the most reliable fatigue assessment.

For future development work, it is recommended to include a sensitivity analysis by attuning the mass or stiffness within the expected range and comparing the response for the lower bound and upper bound estimate. It is anticipated that this will affect the member loads, especially near the mud line, which is prone to fatigue damage.

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Appendix A Input Files

A.1 SACS Model

```
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  SACS MODEL FILE
OPTIONS      MN   DY  SDUC   3 3              PT
SECT
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SECT CON2      TUB                                154.785.000137.105.000
SECT CON3      TUB                                148.802.000137.105.000
SECT CON4      TUB                                155.805.500137.105.000
SECT CON5      TUB                                149.202.200137.105.000
SECT CON6      TUB                                154.204.700137.105.000
SECT CON7      TUB                                148.802.000137.105.000
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SECT DJPG9     PLG                                 50.002.500120.002.000
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SECT DPB       PLG                                 35.003.000 75.002.000
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GRUP B0A         61.000 2.540 20.50 8.0034.50 1    .800.800      0.50N 7.8491.25
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GRUP B1C         50.800 1.270 20.50 8.0035.50 1    .800.800      0.50N 7.849
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GRUP B2D         81.300 2.000 20.50 8.0034.50 1    .800.800      0.50N 7.849
GRUP B3A         50.800 1.588 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP BLA         66.000 2.540 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLB         86.400 3.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLC         66.000 2.540 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLD         86.400 3.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLE         86.400 3.200 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLF         86.400 3.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLG         86.400 3.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLH         45.720 1.905 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLI         45.720 1.905 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP BLJ         45.720 1.905 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP CS1         35.560 1.270 20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP CSA         90.000 2.540 20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP CSB         90.000 2.540 20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP CSC         90.000 2.540 20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP CSZ         90.000 2.540 20.50 8.0024.80 1    1.001.00      0.50N 7.849
GRUP DB1         50.800 1.270 20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP DB2         61.000 2.540 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DB3         81.300 2.500 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DB4         81.300 2.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DB5         40.600 1.900 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DB6         35.600 1.270 20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DB7         27.300 1.270 20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DB8         16.800 0.950 20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DC0 DJPG10              20.50 8.0034.00 1    1.001.00      0.50N 7.849
GRUP DC1 DPG7                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DC2 DPG5                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DC3 DPG4                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DC4 IPE270              20.50 8.0027.50 1    1.001.00 1.00 0.50N 8.191
GRUP DC5 DJPG3               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DC6 DJPG4               20.50 8.0034.00 1    1.001.00      0.50N 7.849
GRUP DC7 DJPG5               20.50 8.0034.00 1    1.001.00      0.50N 7.849
GRUP DC8 IPE600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DC9 DPG1                20.50 8.0034.00 1    1.001.00      0.50N 7.849
GRUP DCE HEB600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DCQ DEQ                 20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DCW HEB600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DF1         45.720 1.270 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DF2         40.640 1.270 20.50 8.0034.50 1    1.001.00      0.50N 7.849
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GRUP DF3          27.300 0.927 20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DF4          21.910 0.953 20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DFB          27.300 1.270 20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DFC UPN220               20.50 8.0024.80 1    1.001.00      0.50N 7.849
GRUP DFG IPE220               20.50 8.0035.50 1    2.001.00      0.50N 7.849
GRUP DFH UPN220               20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DFK IPE220               20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP DFL HEB300               20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP DFP          40.600 1.270 20.50 8.0024.80 1    1.001.00      0.50N 7.849
GRUP DL1          137.10 6.500 20.50 8.0034.00 1    1.201.20 1.00 0.50N 7.849
GRUP DL2          152.40 2.500 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DL3          152.40 2.500 20.50 8.0034.50 1    1.001.00 1.00 0.50N 7.849
GRUP DL4          152.40 2.500 20.50 8.0034.50 1    1.001.00 1.00 0.50N 7.849
GRUP DL5          152.40 2.500 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DL5          152.40 4.000 20.50 8.0034.50 1    1.001.00      0.50N 7.8491.0
GRUP DL6          152.40 4.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DLC DLCON                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DLG          137.10 6.500 20.50 8.0034.00 1    1.201.20 1.00 0.50N 7.849
GRUP DM0 DJPG0                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM1 DPG12                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM2 DPG5                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM3 DPG10                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM4 DPG4                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM5 IPE270               20.50 8.0027.50 1    1.001.00 1.00 0.50N 8.191
GRUP DM6 DJPG2                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM7 IPE600               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM8 HEB600               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DM9 DPG3                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DME HEB600               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DMQ DEQ                  20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DS1          32.380 1.270 20.50 8.0027.50 1    1.001.00      0.50N 8.191
GRUP DS2 HEB300               20.50 8.0034.50 1    1.001.00      0.50N 8.191
GRUP DS3          27.300 1.270 20.50 8.0027.50 1    1.001.00      0.50N 8.191
GRUP DS4          16.800 1.097 20.50 8.0027.50 1    1.001.00      0.50N 8.191
GRUP DV1          121.90 3.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DV2          61.000 3.000 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DV3          50.800 1.430 20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP DV4          50.800 1.270 20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP DW0 DPG7                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW1 DPG12                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW2 DPG5                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW3 DPG9                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW4 IPE270               20.50 8.0027.50 1    1.001.00 1.00 0.50N 8.191
GRUP DW6 DJPG6                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW7 DJPG7                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW8 IPE600               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DW9 DJPG8                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DWB HEB300               20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DWC HEB300               20.50 8.0024.80 1    1.001.00      0.50N 0.001
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GRUP DWD IPE270              20.50 8.0027.50 1    1.001.00      0.50N 0.010
GRUP DWN DPG2                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DWS DJPG11              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DWT         27.300 1.270 20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DWW HEB600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ0 DJPG9               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ1 DPG7                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ2 DPG5                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ3 DPG4                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ4 DPG13               20.50 8.0034.00 1    1.001.00      0.50N 7.849
GRUP DZ5 DPG9                20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ6 IPE270              20.50 8.0027.50 1    1.001.00 1.00 0.50N 8.191
GRUP DZ7 DJPG1               20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ8 IPE600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZ9 HEB300              20.50 8.0027.50 1    1.001.00      0.50N 7.849
GRUP DZB HEB300              20.50 8.0035.50 1    1.001.00      0.50N 7.849
GRUP DZC DPB                 20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZE HEB600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP DZQ DEQ                 20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DZW HEB600              20.50 8.0034.50 1    1.001.00      0.50N 7.849
GRUP L31 CON7                20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP L32 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP L33 CON4                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP L34 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP L35 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP L41 CON4                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP L42 CON3                20.50 8.0034.50 1    1.001.00          F 7.849
GRUP L42 CON5                20.50 8.0034.50 1    1.001.00          F10.4101.76
GRUP L42 CON6                20.50 8.0034.50 1    1.001.00          F10.4100.75
GRUP L43 CON6                20.50 7.8934.50 1    1.001.00          N 7.849
GRUP L44 CON4                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP L45 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP LG2 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.8493.0
GRUP LG2 CON3                20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP LG2 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.8491.35
GRUP LG3 CON7                20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP LG4 CON3                20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP LG4 CON5                20.50 8.0034.50 1    1.001.00      0.50F10.4004.06
GRUP LG4 CON6                20.50 8.0034.00 1    1.001.00      0.50F 8.9612.00
GRUP LG5 CON2                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP LG6         137.20 5.000 20.50 8.0034.50 1    1.001.00      0.50F 7.849
GRUP PL1 CON1                20.50 8.0034.00 1    1.001.00      0.50F 7.849
GRUP R1A         45.700 1.270 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP R1B         45.700 1.270 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP R1C         71.100 1.900 20.50 8.0034.50 1    .800.800      0.50N 7.849
GRUP R1D         71.100 1.900 20.50 8.0034.50 1    .800.800      0.50N 7.849
GRUP R1E         71.100 1.905 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP R1F         71.100 1.905 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP R2A         45.700 1.270 20.50 8.0035.50 1    .800.800      0.50N 7.849
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GRUP R2B          45.700 1.270 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP R2C          71.100 1.900 20.50 8.0034.50 1    .800.800      0.50N 7.849
GRUP R2D          71.100 1.900 20.50 8.0034.50 1    .800.800      0.50N 7.849
GRUP R2E          71.100 1.905 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP R2F          71.100 1.905 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP RAA          45.720 1.588 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP RAB          66.000 1.430 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RAB          66.000 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8491.0
GRUP RAC          66.000 1.430 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RAD          61.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RAD          61.000 2.060 20.50 8.0034.50 1    .900.900      0.50N 7.8491.0
GRUP RAE          61.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RAF          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RAG          50.200 2.240 20.50 8.0035.50 1    .900.900      0.50N11.600
GRUP RAH          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RAJ          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RAJ          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8490.75
GRUP RAK          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RAK          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8490.75
GRUP RAL          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RAL          66.000 2.540 20.50 8.0035.50 1    .900.900      0.50N 7.8491.0
GRUP RAM          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBA          45.720 1.588 20.50 8.0035.50 1    .800.800      0.50N 7.849
GRUP RBB          66.000 1.430 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBB          66.000 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8491.0
GRUP RBC          66.000 1.430 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBD          61.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBD          61.000 2.060 20.50 8.0034.50 1    .900.900      0.50N 7.8491.0
GRUP RBE          61.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBF          50.200 2.240 20.50 8.0034.50 1    .900.900      0.50N11.600
GRUP RBG          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RBH          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RBH          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8490.75
GRUP RBJ          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RBK          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.849
GRUP RBK          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8490.75
GRUP RBL          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBM          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N 7.849
GRUP RBM          66.000 2.540 20.50 8.0034.50 1    .900.900      0.50N 7.8491.0
GRUP RIA          58.500 2.540 20.50 8.0035.50 1   1.001.00      0.50F 0.001
GRUP RS1          25.400 1.270 20.50 8.0035.50 1   1.001.00      0.50N 7.849
GRUP SEA          27.300 1.270 20.50 8.0034.00 1   1.001.00      0.50N 7.849
GRUP SEB          50.000 1.270 20.50 8.0024.80 1   1.001.00      0.50N 7.849
GRUP SEC          50.000 1.270 20.50 8.0024.80 1   1.001.00      0.50N 7.849
GRUP STB PILSTUB              20.50 8.0034.50 9    1.001.00      0.50F 7.849
MEMBER
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PGRUP
PGRUP DP0 1.0000 20.000 0.25024.800                                      0.001
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PGRUP DP1 0.8000 20.000 0.25027.500                                    8.191
PGRUP DP2 0.8000 20.000 0.25027.500                                    8.191
PGRUP DP3 0.8000 20.000 0.25027.500                                    8.191
PGRUP DP4 0.8000 20.000 0.25027.500                                    8.191
PLATE
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JOINT
JOINT    2 -15.238-18.000-42.600                                        1825422
JOINT   20  15.238-18.000-42.600                                        2825424
JOINT   82 -15.238 18.000-42.600                                        3825427
JOINT  100  15.238 18.000-42.600                                        4825431
JOINT  101 -15.073-18.000-41.285                                        5825436
JOINT  103   0.000-18.000-41.285                                        6825442
JOINT  104   0.000 18.000-41.285                                        7825449
JOINT  105 -15.073  0.000-41.285                                        8825457
JOINT  106  15.073  0.000-41.285                                        9825466
JOINT  111   0.000-18.000-32.861                                       10825476
JOINT  112   0.000-18.000-16.566                                       11825487
JOINT  113   0.000-18.000 -1.397                                       12825499
JOINT  114   0.000 18.000-32.861                                       13825512
JOINT  115  -0.001 18.000-16.565                                       14825526
JOINT  116   0.000 18.000 -1.397                                       15825541
JOINT  117 -15.073 -3.090-41.285                                       16825557
JOINT  118 -15.073  3.090-41.285                                       17825574
JOINT  119  15.073-18.000-41.285                                       18825592
JOINT  121  15.073  3.090-41.285                                       19825611
JOINT  122  15.073 -3.090-41.285                                       20825631
JOINT  123   0.852-18.000 -0.788                                       21825652
JOINT  124  -0.852-18.000 -0.788                                       22825674
JOINT  125   0.852 18.000 -0.788                                       23825697
JOINT  126  -0.852 18.000 -0.790                                       24825721
JOINT  181 -15.073 18.000-41.285                                       25825746
JOINT  199  15.073 18.000-41.285                                       26825772
JOINT  201 -13.075-18.000-25.300                                       27825799
JOINT  203   0.000-18.000-25.300                                       28825827
JOINT  204   0.000 18.000-25.300                                       29825856
JOINT  205 -13.075  0.000-25.300                                       30825886
JOINT  206  13.075  0.000-25.300                                       31825917
JOINT  219  13.075-18.000-25.300                                       32825949
JOINT  221  12.870 18.000-23.663                                       33825982
JOINT  222  11.255 18.000-10.736                                       34826016
JOINT  223 -11.255-18.000-10.736                                       35826051
JOINT  224 -11.255 18.000-10.736                                       36826087
JOINT  225  11.255-18.000-10.736                                       37826124
JOINT  226  12.870-18.000-23.663                                       38826162
JOINT  227 -12.870 18.000-23.663                                       39826201
JOINT  228 -12.870-18.000-23.663                                       40826241
JOINT  281 -13.075 18.000-25.300                                       41826282
JOINT  299  13.075 18.000-25.300                                       42826324
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JOINT  303   0.000-18.000 -9.000                                    44826411
JOINT  304   0.000 18.000 -9.000                                    45826456
JOINT  305 -11.038  0.000 -9.000                                    46826502
JOINT  306  11.038  0.000 -9.000                                    47826549
JOINT  319  11.038-18.000 -9.000                                    48826597
JOINT  321  10.707 18.000 -6.355                                    49826646
JOINT  322 -10.845 18.000 -7.452                                    50826696
JOINT  323  10.845-18.000 -7.452                                    51826747
JOINT  324 -10.845-18.000 -7.452                                    52826799
JOINT  381 -11.038 18.000 -9.000                                    53826852
JOINT  399  11.038 18.000 -9.000                                    54826906
JOINT  401  -9.288-18.000  5.000                                    55826961
JOINT  419   9.288-18.000  5.000                                    56827017
JOINT  481  -9.288 18.000  5.000                                    57827074
JOINT  499   9.288 18.000  5.000                                    58827132
JOINT  501  -9.163-18.000  6.000                                    59827191
JOINT  519   9.163-18.000  6.000                                    60827251
JOINT  581  -9.163 18.000  6.000                                    61827312
JOINT  599   9.163 18.000  6.000                                    62827374
JOINT  601  -9.000-18.000  7.300                                    63827437
JOINT  619   9.000-18.000  7.300                                    64827501
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JOINT  699   9.000 18.000  7.300                                    70827906
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JOINT 1002  12.663 18.000  1.000                                    72828049
JOINT 1004   9.788 18.000  1.000                                    73828122
JOINT 1005  12.663 18.000  3.800                                    74828196
JOINT 1006  15.663 18.000  3.800                                    75828271
JOINT 1007  15.663 18.000 -7.000                                    76828347
JOINT 1009  10.788 18.000 -7.000                                    77828424
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JOINT 1013  15.663 26.000 -7.000                                    81828742
JOINT 1015  14.663 24.359 -7.000                                    82828824
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JOINT 1017  12.663 26.000  3.800                                    84828991
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JOINT 1022  15.663 18.000 -1.500                                    87829249
JOINT 1023  15.663 26.000 -1.500                                    88829337
JOINT 1024  15.663 26.000  1.400                                    89829426
JOINT 1025  15.663 19.333 -1.500                                    90829516
JOINT 1026  15.663 20.667 -1.500                                    91829607
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JOINT 1034  15.663 24.667  1.400                                99830371
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JOINT 4376  15.700 18.000 13.300                                    434919816
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JOINT 4519   8.000 18.000 13.300                                532967199
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JOINT 4615   4.000 28.000 13.300                                    580993911
JOINT 4616   5.000 28.000 13.300                                    581994492
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JOINT 4670  -2.000-10.450 15.100                                    607  9949
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JOINT 4672  -2.000-14.500 16.400                                    609 11166
JOINT 4673   3.000-17.000 16.400                                    610 11776
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JOINT 4678   3.000-15.750 16.100                                    615 14841
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JOINT 4695   9.867 24.000 13.300                                    630 24186
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JOINT 4698   9.867 27.000 13.300                                633 26082
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JOINT 4733  -8.000 -4.500 16.800                                663 45537
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JOINT 4739   5.000 25.500 13.300                                669 49536
JOINT 4740   6.000 25.500 13.300                                670 50206
JOINT 4741   5.000 24.000 14.300                                671 50877
JOINT 4742   5.000 25.500 14.300                                672 51549
JOINT 4743   6.000 25.500 14.300                                673 52222
JOINT 4744   6.000 24.000 14.300                                674 52896
JOINT 4745   5.000 24.000 14.800                                675 53571
JOINT 4746   6.000 24.000 14.800                                676 54247
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JOINT 5114   3.000-18.000 19.900                                    727 90049
JOINT 5115   4.000-18.000 19.900                                    728 90777
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JOINT 8190  27.582-38.319 72.739                   2145127006
JOINT 8191  25.682-36.401 72.739                   2146129152
JOINT 8192  27.387-34.712 72.739                   2147131299
JOINT 8193  25.371-36.709 72.739                   2148133447
JOINT 8194  27.715-34.386 72.739                   2149135596
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JOINT 8195  26.526-37.253 72.739                                    2150137746
JOINT 8196  28.231-35.564 72.739                                    2151139897
JOINT 8199   9.177-18.177 35.932                                    2152142049
JOINT 8209  30.556-39.597 77.935                                    2153144202
JOINT 8210  29.704-40.441 77.935                                    2154146356
JOINT 8211  31.409-38.752 77.935                                    2155148511
JOINT 8212  27.804-38.523 77.935                                    2156150667
JOINT 8213  29.509-36.834 77.935                                    2157152824
JOINT 8214  27.493-38.831 77.935                                    2158154982
JOINT 8215  29.837-36.508 77.935                                    2159157141
JOINT 8216  28.648-39.375 77.935                                    2160159301
JOINT 8217  30.353-37.686 77.935                                    2161161462
JOINT 8218  35.549-40.322 84.914                                    2162163624
JOINT 8221  31.294-44.537 84.914                                    2163165787
JOINT 8222  29.173-38.173 84.914                                    2164167951
JOINT 8223  34.486-39.964 84.914                                    2165170116
JOINT 8224  33.423-39.605 84.914                                    2166172282
JOINT 8225  32.361-39.247 84.914                                    2167174449
JOINT 8226  31.298-38.889 84.914                                    2168176617
JOINT 8227  30.235-38.531 84.914                                    2169178786
JOINT 8228  30.940-43.476 84.914                                    2170180956
JOINT 8229  30.587-42.415 84.914                                    2171183127
JOINT 8230  30.233-41.355 84.914                                    2172185299
JOINT 8231  29.880-40.294 84.914                                    2173187472
JOINT 8232  29.526-39.233 84.914                                    2174189646
JOINT 8233  32.003-43.834 84.914                                    2175191821
JOINT 8234  32.712-43.132 84.914                                    2176193997
JOINT 8235  33.421-42.429 84.914                                    2177196174
JOINT 8236  34.130-41.727 84.914                                    2178198352
JOINT 8237  34.840-41.024 84.914                                    2179200531
JOINT 8238  32.710-44.541 84.914                                    2180202711
JOINT 8239  33.419-43.839 84.914                                    2181204892
JOINT 8240  34.128-43.136 84.914                                    2182207074
JOINT 8241  34.837-42.434 84.914                                    2183209257
JOINT 8242  35.547-41.731 84.914                                    2184211441
JOINT 8243  31.646-45.595 84.914                                    2185213626
JOINT 8244  36.609-40.679 84.914                                    2186215812
JOINT 8245  30.150-44.267 84.914                                    2187217999
JOINT 8246  28.736-40.024 84.914                                    2188220187
JOINT 8247  29.796-43.206 84.914                                    2189222376
JOINT 8248  29.443-42.145 84.914                                    2190224566
JOINT 8249  29.089-41.085 84.914                                    2191226757
JOINT 8250  30.501-45.322 84.914                                    2192228949
JOINT 8251  28.382-38.963 84.914                                    2193231142
JOINT 8252  29.966-37.385 84.914                                    2194233336
JOINT 8253  35.279-39.176 84.914                                    2195235531
JOINT 8254  34.217-38.818 84.914                                    2196237727
JOINT 8255  33.154-38.459 84.914                                    2197239924
JOINT 8256  32.091-38.101 84.914                                    2198242122
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JOINT 8257  31.029-37.743 84.914                                    2199244321
JOINT 8258  36.344-39.534 84.914                                    2200246521
JOINT 8259  27.985-37.773 84.914                                    2201248722
JOINT 8260  28.777-36.984 84.914                                    2202250924
JOINT 8261  31.109-36.937 77.935                                    2203253127
JOINT 8265  27.181-37.894 77.935                                    2204255331
JOINT 8266  28.372-37.960 77.935                                    2205257536
JOINT 8267  29.216-38.812 77.935                                    2206259742
JOINT 8268  26.609-36.180 77.935                                    2207261949
JOINT 8269  27.749-37.331 77.935                                    2208264157
JOINT 8272  26.038-36.752 77.935                                    2209266366
JOINT 8273  13.601-22.610 36.365                                    2210268576
JOINT 8274  32.694-41.701 83.131                                    2211270787
JOINT 8275  13.297-22.301 36.615                                    2212272999
JOINT 8276  32.387-41.396 83.381                                    2213275212
JOINT 8277  15.418-24.423 41.811                                    2214277426
JOINT 8278  17.539-26.545 47.007                                    2215279641
JOINT 8279  19.660-28.666 52.204                                    2216281857
JOINT 8280  21.782-30.788 57.400                                    2217284074
JOINT 8281  23.903-32.909 62.596                                    2218286292
JOINT 8282  26.024-35.031 67.792                                    2219288511
JOINT 8283  28.145-37.153 72.989                                    2220290731
JOINT 8284  30.266-39.274 78.185                                    2221292952
JOINT 8285  30.943-40.651 84.914                                    2222295174
JOINT 8286  31.654-39.947 84.914                                    2223297397
JOINT 8287  31.653-41.359 84.914                                    2224299621
JOINT 8288  32.363-40.655 84.914                                    2225301846
JOINT 8289 -16.473-18.000-52.482                  111111            2226304072
JOINT 8290  16.473-18.000-52.482                  111111            2227306299
JOINT 8291 -16.473 18.000-52.482                  111111            2228308527
JOINT 8292  16.474 18.000-52.482                  111111            2229310756
JOINT 8293  -8.250 18.000  5.000                                    2230312986
JOINT 8294  -3.850 18.000  5.000                                    2231315217
JOINT 8295  -1.450 18.000  5.000                                    2232317449
JOINT 8296   5.800 18.000  5.000                                    2233319682
JOINT 8297  -8.350 18.000 -9.000                                    2234321916
JOINT 8298  -1.450 18.000 -9.000                                    2235324151
JOINT 8300  -3.850 18.000 -9.000                                    2236326387
JOINT 8303  -8.350 18.000-25.300                                    2237328624
JOINT 8304  -3.850 18.000-25.300                                    2238330862
JOINT 8305  -1.450 18.000-25.300                                    2239333101
JOINT 8306  11.888 18.000  1.000                                    2240335341
JOINT 8307  11.888 23.843  1.000                                    2241337582
END
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A.2 Fatigue

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SPECTRAL ANALYSIS
FTOPTG7    50.           1.0TTSMHTP  SK      NE EX  6   0.5   18.   7.5   TLPEFT
FTOPT2     PTVC                       -0.81   4.71DE  -41.60  42.72TI
SCF    1.6  3.0  3.0  3.0  1.6  1.6  1.6  1.6 1.6 1.6  1.0  1.0  1.0  1.0
JSLC   101 103 119 117 122 118 121 181 104 199 111 112 113 114 115 116 105 106
JSLC   201 203 219 205 206 281 299 301 303 319 305 306 381 304 399 401 419 481
JSLC   499101210071015101310221025102610271028102910231021830683 07
JSLC  103010311032103310341024100210051001101110171010101610 06
SEAS
FTLOAD   1     0.494           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.50.0002
SCPER    2.50.0231
SCPER    3.50.29160.16290.0002
SCPER    4.50.03860.26360.05680.0002
SCPER    5.5      0.01250.09100.03810.0014
SCPER    6.5            0.00020.00900.00790.00120.0002
SCPER    7.5                  0.0002      0.00020.00020.00020.0002
FTLOAD   2     0.128           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.50.0009
SCPER    2.50.07450.0018
SCPER    3.50.51300.14030.0027
SCPER    4.50.04200.15190.0223
SCPER    5.5      0.00450.03130.00710.0018
SCPER    6.5                  0.00270.0036
FTLOAD   3     0.035           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.5
SCPER    2.50.0888
SCPER    3.50.66120.0724
SCPER    4.50.09540.06580.0033
SCPER    5.5      0.00660.0033
SCPER    6.5                  0.0033
FTLOAD   4     0.034           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.50.0033
SCPER    2.50.0861
SCPER    3.50.64240.0563
SCPER    4.50.10260.0728
SCPER    5.5      0.01990.0132
SCPER    6.5
SCPER    7.5                  0.0033
FTLOAD   5     0.140           SPC
SCATD D                        JS
```

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SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.50.0024
SCPER    2.50.06260.0008
SCPER    3.50.36340.0870
SCPER    4.50.11220.17320.02030.0008
SCPER    5.50.00240.03900.05200.01140.0008
SCPER    6.50.00080.00650.00980.02030.00410.0024
SCPER    7.5            0.00240.00330.00240.00410.00330.0016
SCPER    8.5                        0.00160.0016      0.00330.0008
SCPER    9.5                                    0.00080.00160.0008
FTLOAD   6     0.050           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.50.0069
SCPER    2.50.1304
SCPER    3.50.51030.0755
SCPER    4.50.08470.11210.0229
SCPER    5.5      0.02290.01140.0023
SCPER    6.50.00460.00460.00460.00230.0023
SCPER    7.5      0.0023
FTLOAD   7     0.031           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.5
SCPER    2.50.1606
SCPER    3.50.59850.0620
SCPER    4.50.09120.05110.0146
SCPER    5.5      0.00360.0073
SCPER    6.5      0.0073
SCPER    7.5      0.0036
FTLOAD   8     0.088           SPC
SCATD D                        JS
SCWAV         0.25  0.75  1.25  1.75  2.25  2.75  3.25  3.75  4.25
SCPER    1.50.0069
SCPER    2.50.1304
SCPER    3.50.51030.0755
SCPER    4.50.08470.11210.0229
SCPER    5.5      0.02290.01140.0023
SCPER    6.50.00460.00460.00460.00230.0023
SCPER    7.5      0.0023
END
```

A.3 Wave response

```
WROPT  MNPSL  ALL ES     0.100     0.100   10   -1
PSEL                          BS                   27.9421.590.254 1
PLTTF                       BS                     FQ
TFLCAS   1  38
DAMP      2.0
END

LDOPT       NF+Z    1.03    7.85  -41.60   42.72GLOBMN DYN           NP      K
    SEASTATE FILE FOR WAVE RESPONSE
FILE S
CDM
CDM     1.00 0.821       2.736       0.957       2.736
CDM   200.00 0.821       2.736       0.957       2.736
MGROV
MGROV      0.000  39.100   1.250 -41.600           1.400
MGROV     39.100  44.600   2.500                   1.400
MGROV     44.600  80.000   0.000
GRPOV
GRPOV          B0A                                 1.121.122.912.91
GRPOV          B0B                                 1.121.122.142.14
GRPOV          B0C                                 1.161.162.952.95
GRPOV          B1A                                 1.121.122.932.93
GRPOV          B1D                                 1.121.122.932.93
GRPOV          B1B                                 1.181.182.972.97
GRPOV          B1C                                 1.181.182.972.97
GRPOV          B2A                                 1.111.112.902.90
GRPOV          B2B                                 1.141.142.912.91
GRPOV          B2C                                 1.071.072.892.89
GRPOV          RAA                                 1.201.202.972.97
GRPOV          RBA                                 1.201.202.972.97
GRPOV          RAB                                 1.101.102.912.91
GRPOV          RAM                                 1.101.102.912.91
GRPOV          RAL                                 1.101.102.912.91
GRPOV          RAC                                 1.101.102.912.91
GRPOV          RBB                                 1.101.102.912.91
GRPOV          RBL                                 1.101.102.912.91
GRPOV          RBM                                 1.101.102.912.91
GRPOV          RBC                                 1.101.102.912.91
GRPOV          RAD                                 1.121.122.932.93
GRPOV          RAE                                 1.121.122.932.93
GRPOV          RBD                                 1.121.122.932.93
GRPOV          RBE                                 1.121.122.932.93
GRPOV          RAJ                                 1.151.152.962.96
GRPOV          RAH                                 1.151.152.962.96
GRPOV          RBH                                 1.151.152.962.96
GRPOV          RBJ                                 1.151.152.962.96
GRPOV          R1E                                 1.121.122.912.91
GRPOV          R1F                                 1.121.122.912.91
GRPOV          R1C                                 1.121.122.912.91
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GRPOV          R1D                                  1.121.122.912.91
GRPOV          R2E                                  1.121.122.912.91
GRPOV          R2F                                  1.121.122.912.91
GRPOV          R2C                                  1.121.122.912.91
GRPOV          R2D                                  1.121.122.912.91
GRPOV          R1A                                  1.141.142.962.96
GRPOV          R1B                                  1.141.142.962.96
GRPOV          R2A                                  1.141.142.962.96
GRPOV          R2B                                  1.141.142.962.96
GRPOV          LG2                                  1.081.082.872.87
GRPOV          LG2                                  1.081.082.872.87
GRPOV          LG2                                  1.081.082.872.87
GRPOV          LG3                                  1.081.082.872.87
GRPOV          LG3                                  1.081.082.872.87
GRPOV          LG3                                  1.081.082.872.87
GRPOV          LG4                                  1.051.052.862.86
GRPOV          LG4                                  1.051.052.862.86
GRPOV          LG4                                  1.051.052.862.86
GRPOV          L42                                  1.081.082.872.87
GRPOV          L42                                  1.081.082.872.87
GRPOV          BLH                                  2.742.743.943.94
GRPOV          BLI                                  2.162.163.583.58
GRPOV          BLJ                                  2.012.013.553.55
MEMOV
MEMOV  10301031                                     1.501.503.023.02
MEMOV  10311032                                     1.501.503.023.02
MEMOV  10321033                                     1.501.503.023.02
MEMOV  10331034                                     1.501.503.023.02
MEMOV  10341024                                     1.501.503.023.02
MEMOV  10211022                                     1.841.843.583.58
MEMOV  10181021                                     1.841.843.583.58
MEMOV  10231024                                     1.841.843.583.58
MEMOV  10241016                                     1.841.843.583.58
LOAD
LOADCN
GNTRF   BS 10 0.0625  10.0  0.50              0.00 20AIRCPF
GNTRF   BS  4 0.0625   5.0  0.25              0.00 20AIRCPF
GNTRF   BS 20 0.0625   4.0  0.05              0.00 20AIRCPF
GNTRF   BS 21 0.0625   3.0  0.10              0.00 20AIRCPF
END
```

A.4 Transfer function

```
LDOPT       NF+Z    1.03    7.85  -41.60   42.72GLOBMN DYN            NP      K
    SEA STATE FILE FOR TRANSFER FUNCTION GENERATION ALONG 0,45 AND 90 DEG.,
    FOR 1:25 WAVE STEEPNESS
FILE S
CDM
CDM     1.00 0.600       2.000       0.700       2.000
CDM   200.00 0.600       2.000       0.700       2.000
MGROV
MGROV      0.000  39.100   1.250 -41.600           1.400
MGROV     39.100  44.600   2.500                   1.400
MGROV     44.600  80.000   0.000
GRPOV
GRPOV          B0A                                 0.820.822.072.07
GRPOV          B0B                                 0.920.922.142.14
GRPOV          B0C                                 0.860.862.102.10
GRPOV          B1A                                 0.830.832.082.08
GRPOV          B1D                                 0.830.832.082.08
GRPOV          B1B                                 0.890.892.122.12
GRPOV          B1C                                 0.890.892.122.12
GRPOV          B2A                                 0.810.812.062.06
GRPOV          B2B                                 0.840.842.072.07
GRPOV          B2C                                 0.770.772.042.04
GRPOV          RAA                                 0.900.902.132.13
GRPOV          RBA                                 0.900.902.132.13
GRPOV          RAB                                 0.800.802.062.06
GRPOV          RAM                                 0.800.802.062.06
GRPOV          RAL                                 0.800.802.062.06
GRPOV          RAC                                 0.800.802.062.06
GRPOV          RBB                                 0.800.802.062.06
GRPOV          RBL                                 0.800.802.062.06
GRPOV          RBM                                 0.800.802.062.06
GRPOV          RBC                                 0.800.802.062.06
GRPOV          RAD                                 0.830.832.082.08
GRPOV          RAE                                 0.830.832.082.08
GRPOV          RBD                                 0.830.832.082.08
GRPOV          RBE                                 0.830.832.082.08
GRPOV          RAJ                                 0.850.852.122.12
GRPOV          RAH                                 0.850.852.122.12
GRPOV          RBH                                 0.850.852.122.12
GRPOV          RBJ                                 0.850.852.122.12
GRPOV          R1E                                 0.820.822.072.07
GRPOV          R1F                                 0.820.822.072.07
GRPOV          R1C                                 0.820.822.072.07
GRPOV          R1D                                 0.820.822.072.07
GRPOV          R2E                                 0.820.822.072.07
GRPOV          R2F                                 0.820.822.072.07
GRPOV          R2C                                 0.820.822.072.07
GRPOV          R2D                                 0.820.822.072.07
GRPOV          R1A                                 0.840.842.122.12
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GRPOV          R1B                                  0.840.842.122.12
GRPOV          R2A                                  0.840.842.122.12
GRPOV          R2B                                  0.840.842.122.12
GRPOV          LG2                                  0.780.782.022.02
GRPOV          LG2                                  0.780.782.022.02
GRPOV          LG2                                  0.780.782.022.02
GRPOV          LG3                                  0.780.782.022.02
GRPOV          LG4                                  0.750.752.012.01
GRPOV          LG4                                  0.750.752.012.01
GRPOV          LG4                                  0.750.752.012.01
GRPOV          L42                                  0.780.782.022.02
GRPOV          L42                                  0.780.782.022.02
GRPOV          BLH                                  2.442.443.093.09
GRPOV          BLI                                  1.871.872.732.73
GRPOV          BLJ                                  1.611.612.672.67
MEMOV
MEMOV  10301031                                     1.151.152.172.17
MEMOV  10311032                                     1.151.152.172.17
MEMOV  10321033                                     1.151.152.172.17
MEMOV  10331034                                     1.151.152.172.17
MEMOV  10341024                                     1.151.152.172.17
MEMOV  10211022                                     1.551.552.742.74
MEMOV  10181021                                     1.551.552.742.74
MEMOV  10231024                                     1.551.552.742.74
MEMOV  10241016                                     1.551.552.742.74
LOAD
LOADCN
GNTRF   BS 10  0.040 10.00 0.500            0.00   20AIRCPF
GNTRF   BS 10  0.040 5.000 0.250            0.00   20AIRCPF
GNTRF   BS 16  0.040 2.500 0.100            0.00   20AIRCPF
LOADCN
GNTRF   BS 10  0.040 10.00 0.500           45.00  20AIRCPF
GNTRF   BS 10  0.040 5.000 0.250           45.00  20AIRCPF
GNTRF   BS 16  0.040 2.500 0.100           45.00  20AIRCPF
LOADCN
GNTRF   BS 10  0.040 10.00 0.500           90.00  20AIRCPF
GNTRF   BS 10  0.040 5.000 0.250           90.00  20AIRCPF
GNTRF   BS 16  0.040 2.500 0.100           90.00  20AIRCPF
END
```

A.5 Response function

```
LDOPT       NF+Z   1.030    7.85    0.00    0.00GLOBMN DYN            NP      K
    RESPONSE FUNCTION (RMS) DETERMINATION
OPTIONS      MN   DY  SDUC   3 3              PT
SECT
*
GRUP
GRUP B0A         61.000 1.905 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B0A         61.000 2.540 20.50 8.0034.50 1    .800.800      0.50N0.00011.25
GRUP B0B         61.000 1.905 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B0B         61.000 2.540 20.50 8.0034.50 1    .800.800      0.50N0.00011.06
GRUP B0C         61.000 1.270 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP B0D         61.000 2.540 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B1A         61.000 1.270 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP B1A         61.000 2.060 20.50 8.0034.50 1    .800.800      0.50N0.00011.25
GRUP B1B         101.60 4.500 20.50 8.0035.50 1    .800.800      0.50N0.00011.75
GRUP B1B CONB0B              20.50 8.0035.50 1    .800.800      0.50N0.00010.81
GRUP B1B         61.000 1.270 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP B1C         50.800 1.270 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP B1D         61.000 1.270 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP B2A         81.300 2.000 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B2A         81.300 2.540 20.50 8.0034.50 1    .800.800      0.50N0.00011.25
GRUP B2B         81.300 2.200 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B2B         81.300 2.540 20.50 8.0034.50 1    .800.800      0.50N0.00011.75
GRUP B2C         66.000 1.750 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B2D         81.300 2.000 20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP B3A         50.800 1.270 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP BLA         66.000 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLB         86.400 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLC         66.000 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLD         86.400 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLE         86.400 3.000 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLF         86.400 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLG         86.400 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLH         45.720 1.905 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLI         45.720 1.905 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP BLJ         45.720 1.905 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP CS1         50.800 1.270 20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP CSA         90.000 2.540 20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP CSB         90.000 2.540 20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP CSC         90.000 2.540 20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP CSZ         90.000 2.540 20.50 8.0024.80 1    1.001.00      0.50N0.0001
GRUP DB1         50.800 1.270 20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP DB2         61.000 2.540 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DB3         81.300 2.500 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DB4         81.300 2.000 20.50 8.0034.50 1    1.001.00      0.50N0.0001
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GRUP DB5          40.600 1.900 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DB6          35.600 1.270 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DB7          27.300 1.270 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DB8          16.800 0.950 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DC0 DJPG10               20.50 8.0034.00 1    1.001.00      0.50N0.0001
GRUP DC1 DPG7                 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DC2 DPG5                 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DC3 DPG4                 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DC4 IPE270               20.50 8.0027.50 1    1.001.00 1.00 0.50N0.0001
GRUP DC5 DJPG3                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DC6 DJPG4                20.50 8.0034.00 1    1.001.00      0.50N0.0001
GRUP DC7 DJPG5                20.50 8.0034.00 1    1.001.00      0.50N0.0001
GRUP DC8 IPE600               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DC9 DPG1                 20.50 8.0034.00 1    1.001.00      0.50N0.0001
GRUP DCE HEB600               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DCQ DEQ                  20.50 8.0024.80 1    1.001.00      0.50N0.0001
GRUP DCW HEB600               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DF1          45.720 1.270 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DF2          40.640 1.270 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DF3          27.300 0.927 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DF4          21.910 0.953 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DFB          27.300 1.270 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DFC UPN220               20.50 8.0024.80 1    1.001.00      0.50N0.0001
GRUP DFG IPE220               20.50 8.0035.50 1    2.001.00      0.50N0.0001
GRUP DFH UPN220               20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DFK IPE220               20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP DFL HEB300               20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP DFP          40.600 1.270 20.50 8.0024.80 1    1.001.00      0.50N0.0001
GRUP DL1          137.10 6.500 20.50 8.0034.00 1    1.201.20 1.00 0.50N0.0001
GRUP DL2          152.40 2.500 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DL3          152.40 2.500 20.50 8.0034.50 1    1.001.00 1.00 0.50N0.0001
GRUP DL4          152.40 2.500 20.50 8.0034.50 1    1.001.00 1.00 0.50N0.0001
GRUP DL5          152.40 2.500 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DL5          152.40 4.000 20.50 8.0034.50 1    1.001.00      0.50N0.00011.0
GRUP DL6          152.40 4.000 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DLC DLCON                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DLG          137.10 6.500 20.50 8.0034.00 1    1.201.20 1.00 0.50N0.0001
GRUP DM0 DJPG0                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM1 DPG12                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM2 DPG5                 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM3 DPG10                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM4 DPG4                 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM5 IPE270               20.50 8.0027.50 1    1.001.00 1.00 0.50N0.0001
GRUP DM6 DJPG2                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM7 IPE600               20.50 8.0034.50 1    1.001.00      0.50N0.0001
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GRUP DM8 HEB600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DM9 DPG3                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DME HEB600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DMQ DEQ                 20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DS1         32.380 1.270 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DS2 HEB300              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DS3         27.300 1.270 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DS4         16.800 1.097 20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DV1         121.90 3.000 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DV2         61.000 3.000 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DV3         50.800 1.430 20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP DV4         50.800 1.270 20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP DW0 DPG7                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW1 DPG12               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW2 DPG5                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW3 DPG9                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW4 IPE270              20.50 8.0027.50 1    1.001.00 1.00 0.50N0.0001
GRUP DW6 DJPG6               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW7 DJPG7               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW8 IPE600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DW9 DJPG8               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DWB HEB300              20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DWC HEB300              20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DWD IPE270              20.50 8.0027.50 1    1.001.00      0.50N 0.010
GRUP DWN DPG2                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DWS DJPG11              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DWT         27.300 1.270 20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DWW HEB600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ0 DJPG9               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ1 DPG7                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ2 DPG5                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ3 DPG4                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ4 DPG13               20.50 8.0034.00 1    1.001.00      0.50N0.0001
GRUP DZ5 DPG9                20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ6 IPE270              20.50 8.0027.50 1    1.001.00 1.00 0.50N0.0001
GRUP DZ7 DJPG1               20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ8 IPE600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZ9 HEB300              20.50 8.0027.50 1    1.001.00      0.50N0.0001
GRUP DZB HEB300              20.50 8.0035.50 1    1.001.00      0.50N0.0001
GRUP DZC DPB                 20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZE HEB600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP DZQ DEQ                 20.50 8.0024.80 1    1.001.00      0.50N 0.001
GRUP DZW HEB600              20.50 8.0034.50 1    1.001.00      0.50N0.0001
GRUP L31 CON7                20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP L32 CON2                20.50 8.0034.00 1    1.001.00      0.50F0.0001
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GRUP L33 CON4                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP L34 CON2                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP L35 CON2                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP L41 CON4                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP L42 CON3                  20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP L42 CON5                  20.50 8.0034.50 1    1.001.00      0.50F0.00012.02
GRUP L43 CON5                  20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP L43 CON6                  20.50 8.0034.00 1    1.001.00      0.50F0.00012.0
GRUP L44 CON4                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP L45 CON2                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP LG2 CON2                  20.50 8.0034.00 1    1.001.00      0.50F0.00013.0
GRUP LG2 CON3                  20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP LG2 CON2                  20.50 8.0034.00 1    1.001.00      0.50F0.00011.35
GRUP LG3 CON7                  20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP LG4 CON3                  20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP LG4 CON5                  20.50 8.0034.50 1    1.001.00      0.50F0.00014.06
GRUP LG4 CON6                  20.50 8.0034.00 1    1.001.00      0.50F0.00012.00
GRUP LG5 CON2                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP LG6         137.20 5.000  20.50 8.0034.50 1    1.001.00      0.50F0.0001
GRUP PL1 CON1                  20.50 8.0034.00 1    1.001.00      0.50F0.0001
GRUP R1A         45.700 1.270  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R1B         45.700 1.270  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R1C         71.100 1.900  20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP R1D         71.100 1.900  20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP R1E         71.100 1.430  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R1F         71.100 1.430  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R2A         45.700 1.270  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R2B         45.700 1.270  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R2C         71.100 1.900  20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP R2D         71.100 1.900  20.50 8.0034.50 1    .800.800      0.50N0.0001
GRUP R2E         71.100 1.430  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP R2F         71.100 1.430  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP RAA         61.000 1.590  20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP RAB         66.000 1.430  20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RAB         66.000 2.060  20.50 8.0034.50 1    .900.900      0.50N0.00011.0
GRUP RAC         66.000 1.430  20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RAD         61.000 1.270  20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RAD         61.000 2.060  20.50 8.0034.50 1    .900.900      0.50N0.00011.0
GRUP RAE         61.000 1.270  20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RAF         50.800 1.905  20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RAG         49.600 1.305  20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RAH         50.800 1.905  20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RAJ         50.800 1.905  20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RAJ         50.800 2.540  20.50 8.0034.50 1    .900.900      0.50N0.00010.75
GRUP RAK         50.800 1.905  20.50 8.0034.50 1    .900.900      0.50N0.0001
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GRUP RAK          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N0.00010.75
GRUP RAL          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RAL          66.000 2.062 20.50 8.0035.50 1    .900.900      0.50N0.00011.0
GRUP RAM          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBA          61.000 1.590 20.50 8.0035.50 1    .800.800      0.50N0.0001
GRUP RBB          66.000 1.430 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBB          66.000 2.060 20.50 8.0034.50 1    .900.900      0.50N0.00011.0
GRUP RBC          66.000 1.430 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBD          61.000 1.270 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBD          61.000 2.060 20.50 8.0034.50 1    .900.900      0.50N0.00011.0
GRUP RBE          61.000 1.270 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBF          49.600 1.305 20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RBG          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RBH          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RBH          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N0.00010.75
GRUP RBJ          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RBK          50.800 1.905 20.50 8.0034.50 1    .900.900      0.50N0.0001
GRUP RBK          50.800 2.540 20.50 8.0034.50 1    .900.900      0.50N0.00010.75
GRUP RBL          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBM          66.000 1.270 20.50 8.0035.50 1    .900.900      0.50N0.0001
GRUP RBM          66.000 2.062 20.50 8.0034.50 1    .900.900      0.50N0.00011.0
GRUP RIA          58.500 2.540 20.50 8.0035.50 1   1.001.00      0.50F 0.001
GRUP RS1          25.400 1.270 20.50 8.0035.50 1   1.001.00      0.50N0.0001
GRUP SEA          27.300 1.270 20.50 8.0034.00 1   1.001.00      0.50N0.0001
GRUP SEB          50.000 1.270 20.50 8.0024.80 1   1.001.00      0.50N0.0001
GRUP SEC          50.000 1.270 20.50 8.0024.80 1   1.001.00      0.50N0.0001
GRUP STB PILSTUB              20.50 8.0034.50 9   1.001.00      0.50F0.0001
MEMBER
*
PGRUP
PGRUP DP0 1.0000 20.000 0.25024.800                                          0.001
PGRUP DP1 0.8000 20.000 0.25027.500                                          0.001
PGRUP DP2 0.8000 20.000 0.25027.500                                          0.001
PGRUP DP3 0.8000 20.000 0.25027.500                                          0.001
PGRUP DP4 0.8000 20.000 0.25027.500                                          0.001
PLATE
*
JOINT
*
CDM
CDM     1.00 0.853       0.001       0.995       0.001
CDM   200.00 0.853       0.001       0.995       0.001
MGROV
*
GRPOV
```

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*
MEMOV
MEMOV  10301031                                  1.501.503.023.02
MEMOV  10311032                                  1.501.503.023.02
MEMOV  10321033                                  1.501.503.023.02
MEMOV  10331034                                  1.501.503.023.02
MEMOV  10341024                                  1.501.503.023.02
MEMOV  10211022                                  1.841.843.583.58
MEMOV  10181021                                  1.841.843.583.58
MEMOV  10231024                                  1.841.843.583.58
MEMOV  10241016                                  1.841.843.583.58
*
LOAD
END


WROPT  MNPSL  MAXS                        10   -1
PLTTF                      BSB                    PF
DAMP       100.
WSPEC     JS  0.737  3.750                              1  36
WSPEC     JS  1.311  5.000                             37  72
WSPEC     JS  1.311  5.000                             73 108
END
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A.6 Deterministic base shear range

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LDOPT       NF+Z    1.03    7.85  -41.60   42.72GLOBMN                NP      K
    SEA STATE FOR SINGLE WAVE CORRESPONDING TO CENTER OF FATIGUE
LCSEL ST          SW1  SW2  SW3
FILE S
CDM
CDM     1.00 0.600       2.000       0.700       2.000
CDM   200.00 0.600       2.000       0.700       2.000
MGROV
MGROV      0.000  39.100   1.250 -41.600           1.400
MGROV     39.100  44.600   2.500                   1.400
MGROV     44.600  80.000   0.000
GRPOV
GRPOV          B0A                                 0.820.822.072.07
GRPOV          B0B                                 0.920.922.142.14
GRPOV          B0C                                 0.860.862.102.10
GRPOV          B1A                                 0.830.832.082.08
GRPOV          B1D                                 0.830.832.082.08
GRPOV          B1B                                 0.890.892.122.12
GRPOV          B1C                                 0.890.892.122.12
GRPOV          B2A                                 0.810.812.062.06
GRPOV          B2B                                 0.840.842.072.07
GRPOV          B2C                                 0.770.772.042.04
GRPOV          RAA                                 0.900.902.132.13
GRPOV          RBA                                 0.900.902.132.13
GRPOV          RAB                                 0.800.802.062.06
GRPOV          RAM                                 0.800.802.062.06
GRPOV          RAL                                 0.800.802.062.06
GRPOV          RAC                                 0.800.802.062.06
GRPOV          RBB                                 0.800.802.062.06
GRPOV          RBL                                 0.800.802.062.06
GRPOV          RBM                                 0.800.802.062.06
GRPOV          RBC                                 0.800.802.062.06
GRPOV          RAD                                 0.830.832.082.08
GRPOV          RAE                                 0.830.832.082.08
GRPOV          RBD                                 0.830.832.082.08
GRPOV          RBE                                 0.830.832.082.08
GRPOV          RAJ                                 0.850.852.122.12
GRPOV          RAH                                 0.850.852.122.12
GRPOV          RBH                                 0.850.852.122.12
GRPOV          RBJ                                 0.850.852.122.12
GRPOV          R1E                                 0.820.822.072.07
GRPOV          R1F                                 0.820.822.072.07
GRPOV          R1C                                 0.820.822.072.07
GRPOV          R1D                                 0.820.822.072.07
GRPOV          R2E                                 0.820.822.072.07
GRPOV          R2F                                 0.820.822.072.07
GRPOV          R2C                                 0.820.822.072.07
GRPOV          R2D                                 0.820.822.072.07
GRPOV          R1A                                 0.840.842.122.12
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GRPOV          R1B                                0.840.842.122.12
GRPOV          R2A                                0.840.842.122.12
GRPOV          R2B                                0.840.842.122.12
GRPOV          LG2                                0.780.782.022.02
GRPOV          LG2                                0.780.782.022.02
GRPOV          LG2                                0.780.782.022.02
GRPOV          LG3                                0.780.782.022.02
GRPOV          LG3                                0.780.782.022.02
GRPOV          LG3                                0.780.782.022.02
GRPOV          LG4                                0.750.752.012.01
GRPOV          LG4                                0.750.752.012.01
GRPOV          LG4                                0.750.752.012.01
GRPOV          L42                                0.780.782.022.02
GRPOV          L42                                0.780.782.022.02
GRPOV          BLH                                2.442.443.093.09
GRPOV          BLI                                1.871.872.732.73
GRPOV          BLJ                                1.611.612.672.67
MEMOV
MEMOV  10301031                                   1.151.152.172.17
MEMOV  10311032                                   1.151.152.172.17
MEMOV  10321033                                   1.151.152.172.17
MEMOV  10331034                                   1.151.152.172.17
MEMOV  10341024                                   1.151.152.172.17
MEMOV  10211022                                   1.551.552.742.74
MEMOV  10181021                                   1.551.552.742.74
MEMOV  10231024                                   1.551.552.742.74
MEMOV  10241016                                   1.551.552.742.74
DUMMY RISER
KEEP    101  201  301  501
DELETE 1101 1102 1103 1104
LOAD
LOADCN SW1
WAVE
WAVE 1.0AIRC 1.371       3.750       0.000       D          10.  36MS10 1 0
LOADCN SW2
WAVE
WAVE 1.0AIRC 2.438       5.000       45.000      D          10.  36MS10 1 0
LOADCN SW3
WAVE
WAVE 1.0AIRC 2.438       5.000       90.000      D          10.  36MS10 1 0
END
```

A.7 Pile-stub generation

```
LDOPT       NF+Z   1.030    7.85  -41.60  42.720GLOBMN               NP      K
    INPLACCE ANALYSIS FOR PILESTUB GENERATION
OPTIONS      MN   PI  SDUC   3 3              PT
LCSEL ST        CSW1 CSW2 CSW3
UCPART     0.00 0.80 0.80 1.00 1.001000.
SECT
*
GRUP
*
MEMBER
*
PGRUP
*
PLATE
*
JOINT
*
CDM
CDM     1.00 0.600       2.000       0.700       2.000
CDM   200.00 0.600       2.000       0.700       2.000
MGROV
*
GRPOV
*
MEMOV
*
LOAD
*
LOADCN SW1
WAVE
WAVE 1.0AIRC 1.371       3.750        0.000       D          10.  36MS10 1 0
LOADCN SW2
WAVE
WAVE 1.0AIRC 2.438       5.000        45.000      D          10.  36MS10 1 0
LOADCN SW3
WAVE
WAVE 1.0AIRC 2.438       5.000        90.000      D          10.  36MS10 1 0
LCOMB
*
LCOMB CSW1 C005 1.000 SW1 1.000
LCOMB CSW2 C005 1.000 SW2 1.000
LCOMB CSW3 C005 1.000 SW3 1.000
*
END

PSIOPT +ZMN           SM0.00254 0.0001  200        PT        100        7.849047
PLTRQ SD        DL             AL                 UC
PLGRUP
PLGRUP PL1         137.16  5.00   20.    8.  34.0    67.5             1.0 1.477
```

```
PILE
PILE     2 101 PL1                                                  SOL1 SOL1
PILE    20 119 PL1                                                  SOL1 SOL1
PILE    82 181 PL1                                                  SOL1 SOL1
PILE   100 199 PL1                                                  SOL1 SOL1
SOIL
SOIL
SOIL TZAXIAL HEAD 22                0.1SOL1
SOIL         SLOCSM   7   0.00        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .002   2.4  .003   4.7 0.005   8.7 0.006  12.2
SOIL         T-Z  0.006  15.2 0.004  30.5
SOIL         SLOCSM   7   1.00        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .006   2.4  .011   4.7 0.016   8.7 0.019  12.2
SOIL         T-Z  0.021  15.2 0.015  30.5
SOIL         SLOCSM   7   1.01        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .026   2.4  .043   4.7 0.064   8.7 0.077  12.2
SOIL         T-Z  0.085  15.2 0.060  30.5
SOIL         SLOCSM   7   5.50        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .041   2.4  .069   4.7 0.104   8.7 0.124  12.2
SOIL         T-Z  0.138  15.2 0.097  30.5
SOIL         SLOCSM   7   5.51        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .088   2.4  .147   4.7 0.220   8.7 0.264  12.2
SOIL         T-Z  0.294  15.2 0.206  30.5
SOIL         SLOCSM   7  11.40        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .177   2.4  .295   4.7 0.443   8.7 0.532  12.2
SOIL         T-Z  0.591  15.2 0.413  30.5
SOIL         SLOCSM   7  11.41        0.0209            SAND
SOIL         T-Z  0.000  0.00  .024    .5  .049   1.0 0.073   1.5 0.098   2.0
SOIL         T-Z  0.122   2.5 0.122   5.1
SOIL         SLOCSM   7  20.00        0.0209            SAND
SOIL         T-Z  0.000  0.00  .046    .5  .091   1.0 0.137   1.5 0.182   2.0
SOIL         T-Z  0.228   2.5 0.228   5.1
SOIL         SLOCSM   7  20.01        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .162   2.4  .270   4.7 0.406   8.7 0.487  12.2
SOIL         T-Z  0.541  15.2 0.379  30.5
SOIL         SLOCSM   7  36.00        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .271   2.4  .451   4.7 0.677   8.7 0.812  12.2
SOIL         T-Z  0.903  15.2 0.632  30.5
SOIL         SLOCSM   7  36.01        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .271   2.4  .452   4.7 0.678   8.7 0.814  12.2
SOIL         T-Z  0.904  15.2 0.633  30.5
SOIL         SLOCSM   7  40.10        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .279   2.4  .465   4.7 0.697   8.7 0.837  12.2
SOIL         T-Z  0.930  15.2 0.651  30.5
SOIL         SLOCSM   7  40.11        0.0209            SAND
SOIL         T-Z  0.000  0.00  .091    .5  .182   1.0 0.273   1.5 0.364   2.0
SOIL         T-Z  0.455   2.5 0.455   5.1
SOIL         SLOCSM   7  63.00        0.0209            SAND
SOIL         T-Z  0.000  0.00  .091    .5  .182   1.0 0.273   1.5 0.364   2.0
```

```
SOIL         T-Z  0.455   2.5 0.455   5.1
SOIL         SLOCSM   7  63.01        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .385   2.4  .641   4.7 0.962   8.7 1.155  12.2
SOIL         T-Z  1.283  15.2 0.898  30.5
SOIL         SLOCSM   7  75.00        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .421   2.4  .702   4.7 1.053   8.7 1.263  12.2
SOIL         T-Z  1.403  15.2 0.982  30.5
SOIL         SLOCSM   7  75.01        0.0209            SAND
SOIL         T-Z  0.000  0.00  .091    .5  .182   1.0 0.273   1.5 0.364   2.0
SOIL         T-Z  0.455   2.5 0.455   5.1
SOIL         SLOCSM   7  81.00        0.0209            SAND
SOIL         T-Z  0.000  0.00  .091    .5  .182   1.0 0.273   1.5 0.364   2.0
SOIL         T-Z  0.455   2.5 0.455   5.1
SOIL         SLOCSM   7  81.01        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .392   2.4  .654   4.7 0.980   8.7 1.176  12.2
SOIL         T-Z  1.307  15.2 0.915  30.5
SOIL         SLOCSM   7  88.00        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .409   2.4  .682   4.7 1.023   8.7 1.227  12.2
SOIL         T-Z  1.363  15.2 0.954  30.5
SOIL         SLOCSM   7  88.01        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .436   2.4  .726   4.7 1.089   8.7 1.307  12.2
SOIL         T-Z  1.452  15.2 1.017  30.5
SOIL         SLOCSM   7  91.00        0.0209            CLAY
SOIL         T-Z  0.000  0.00  .529   2.4  .882   4.7 1.323   8.7 1.587  12.2
SOIL         T-Z  1.764  15.2 1.235  30.5
SOIL BEARING HEAD 20                  0.1SOL1
SOIL         SLOC     6   55.0        0.0548SAND
SOIL         T-Z    0.0   0.0  2.96  3.00  5.93 19.80  8.89 64.00 10.67 111.3
SOIL         T-Z  11.86 152.4
SOIL         SLOC     6   57.0        0.0548SAND
SOIL         T-Z    0.0   0.0  2.96  3.00  5.93 19.80  8.89 64.00 10.67 111.3
SOIL         T-Z  11.86 152.4
SOIL         SLOC     6   59.0        0.0548SAND
SOIL         T-Z    0.0   0.0  2.85  3.00  5.70 19.80  8.55 64.00 10.26 111.3
SOIL         T-Z  11.40 152.4
SOIL         SLOC     6   61.0        0.0548SAND
SOIL         T-Z    0.0   0.0  2.45  3.00  4.90 19.80  7.35 64.00  8.82 111.3
SOIL         T-Z   9.80 152.4
SOIL         SLOC     6   63.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.05  3.00  4.10 19.80  6.16 64.00  7.39 111.3
SOIL         T-Z   8.21 152.4
SOIL         SLOC     6   65.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.05  3.00  4.10 19.80  6.16 64.00  7.39 111.3
SOIL         T-Z   8.21 152.4
SOIL         SLOC     6   67.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.05  3.00  4.10 19.80  6.16 64.00  7.39 111.3
SOIL         T-Z   8.21 152.4
SOIL         SLOC     6   69.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.05  3.00  4.10 19.80  6.16 64.00  7.39 111.3
```

```
SOIL         T-Z   8.21 152.4
SOIL         SLOC     6   71.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.05  3.00  4.10 19.80  6.16 64.00  7.39 111.3
SOIL         T-Z   8.21 152.4
SOIL         SLOC     6   73.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.05  3.00  4.10 19.80  6.16 64.00  7.39 111.3
SOIL         T-Z   8.21 152.4
SOIL         SLOC     6   75.0        0.0548SAND
SOIL         T-Z    0.0   0.0  3.31  3.00  6.61 19.80  9.92 64.00 11.90 111.3
SOIL         T-Z  13.23 152.4
SOIL         SLOC     6   77.0        0.0548SAND
SOIL         T-Z    0.0   0.0  3.82  3.00  7.64 19.80 11.45 64.00 13.74 111.3
SOIL         T-Z  15.27 152.4
SOIL         SLOC     6   79.0        0.0548SAND
SOIL         T-Z    0.0   0.0  2.92  3.00  5.84 19.80  8.76 64.00 10.51 111.3
SOIL         T-Z  11.67 152.4
SOIL         SLOC     6   81.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  1.64  3.00  3.28 19.80  4.93 64.00  5.91 111.3
SOIL         T-Z   6.57 152.4
SOIL         SLOC     6   83.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  1.64  3.00  3.28 19.80  4.93 64.00  5.91 111.3
SOIL         T-Z   6.57 152.4
SOIL         SLOC     6   85.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  1.64  3.00  3.28 19.80  4.93 64.00  5.91 111.3
SOIL         T-Z   6.57 152.4
SOIL         SLOC     6   87.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  1.64  3.00  3.28 19.80  4.93 64.00  5.91 111.3
SOIL         T-Z   6.57 152.4
SOIL         SLOC     6   88.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  1.74  3.00  3.49 19.80  5.23 64.00  6.28 111.3
SOIL         T-Z   6.98 152.4
SOIL         SLOC     6   89.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  1.96  3.00  3.92 19.80  5.88 64.00  7.05 111.3
SOIL         T-Z   7.84 152.4
SOIL         SLOC     6   91.0        0.0548CLAY
SOIL         T-Z    0.0   0.0  2.67  3.00  5.34 19.80  8.00 64.00  9.60 111.3
SOIL         T-Z  10.67 152.4
SOIL LATERAL HEAD 28        152.4    0.1SOL1 CYCLIC P-Y DATA
SOIL         SLOCSM   5   0.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.007  12.6 0.011  57.1 0.016 171.4 0.000 857.2
SOIL         SLOCSM   5   1.30      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.093   8.4 0.155  38.1 0.223 114.3 0.014 571.5
SOIL         SLOCSM   5   2.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.100   8.4 0.166  38.1 0.239 114.3 0.023 571.5
SOIL         SLOCSM   5   3.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.110   8.4 0.182  38.1 0.263 114.3 0.037 571.5
SOIL         SLOCSM   5   4.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.120   8.4 0.199  38.1 0.287 114.3 0.054 571.5
SOIL         SLOCSM   5   5.00      10.0                CLAY
```

```
SOIL         P-Y    0.0   0.0 0.130   8.4 0.216  38.1 0.311 114.3 0.072 571.5
SOIL         SLOCSM   5   6.20      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.383   8.4 0.635  38.1 0.915 114.3 0.191 571.5
SOIL         SLOCSM   5   7.50      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.482   8.4 0.799  38.1 1.152 114.3 0.283 571.5
SOIL         SLOCSM   5   8.50      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.563   8.4 0.933  38.1 1.346 114.3 0.368 571.5
SOIL         SLOCSM   5  10.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.694   8.4 1.149  38.1 1.657 114.3 0.522 571.5
SOIL         SLOCSM   5  11.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.786   8.4 1.302  38.1 1.878 114.3 0.643 571.5
SOIL         SLOCSM   5  12.50      10.0                SAND
SOIL         P-Y    0.0   0.0 1.401   3.4 3.048  14.4 3.048  25.4 3.048  57.1
SOIL         SLOCSM   5  15.00      10.0                SAND
SOIL         P-Y    0.0   0.0 2.025   4.1 3.048  14.7 3.048  25.4 3.048  57.1
SOIL         SLOCSM   5  16.50      10.0                SAND
SOIL         P-Y    0.0   0.0 2.454   4.5 3.048  15.0 3.048  25.4 3.048  57.1
SOIL         SLOCSM   5  18.00      10.0                SAND
SOIL         P-Y    0.0   0.0 2.923   4.9 3.048  15.2 3.048  25.4 3.048  57.1
SOIL         SLOCSM   5  20.00      10.0                SAND
SOIL         P-Y    0.0   0.0 3.048   4.4 3.048  15.4 3.048  25.4 3.048  57.1
SOIL         SLOCSM   5  20.01      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.798   8.4 1.323  38.1 1.907 114.3 1.253 571.5
SOIL         SLOCSM   5  22.50      10.0                CLAY
SOIL         P-Y    0.0   0.0 0.928   8.4 1.538  38.1 2.218 114.3 1.620 571.5
SOIL         SLOCSM   5  25.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.068   8.4 1.769  38.1 2.551 114.3 2.048 571.5
SOIL         SLOCSM   5  27.50      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.215   8.4 2.014  38.1 2.904 114.3 2.541 571.5
SOIL         SLOCSM   5  29.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.308   8.4 2.168  38.1 3.126 114.3 2.870 571.5
SOIL         SLOCSM   5  31.50      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.470   8.4 2.436  38.1 3.513 114.3 3.475 571.5
SOIL         SLOCSM   5  33.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.539   8.4 2.550  38.1 3.678 114.3 3.678 571.5
SOIL         SLOCSM   5  37.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.656   8.4 2.743  38.1 3.956 114.3 3.956 571.5
SOIL         SLOCSM   5  39.00      10.0                CLAY
SOIL         P-Y    0.0   0.0 1.656   8.4 2.743  38.1 3.956 114.3 3.956 571.5
SOIL         SLOCSM   5  42.00      10.0                SAND
SOIL         P-Y    0.0   0.0 8.906   6.3 9.906  12.7 9.906  25.4 9.906  57.1
SOIL         SLOCSM   5  45.00      10.0                SAND
SOIL         P-Y    0.0   0.0 9.545   6.3 9.906  12.7 9.906  25.4 9.906  57.1
SOIL         SLOCSM   5  50.00      10.0                SAND
SOIL         P-Y    0.0   0.0 9.906   5.7 9.906  12.7 9.906  25.4 9.906  57.1
END

PLOPT MN    100  100 0.00254       7.850  PT
PLTRQ SD        DL             AL                 UC
```

```
PLGRUP
PLGRUP PL1          137.16  5.00   20.    8.  34.0    67.5              1.0 1.477
PILE
PILE     2 101 PL1                                                 SOL1 SOL1
SOIL
*
PLSTUB   F  51          212.29    565.00  18339.14      1.66
END
```

```
PLOPT MN    100  100 0.00254       7.850  PT
PLTRQ SD        DL             AL                  UC
PLGRUP
PLGRUP PL1         137.16  5.00   20.    8.  34.0    67.5              1.0 1.477
PILE
PILE     2 101 PL1                                                SOL1 SOL1
SOIL
*
PLSTUB   F  51          212.29    565.00  18339.14      1.66
END

          ************************** SACS SAMPLE CARD IMAGES **************************
                   1         2         3         4         5         6         7         8
          12345678901234567890123456789012345678901234567890123456789012345678901234567890

          SECT PILSTUB   PRI620.196503500.6503500.6503500. 10.000     10.000
          GRUP STB PILSTUB
          MEMBER2  51   2 STBSK
          MEMBER OFFSETS                                        154.0
          JOINT    2 0.0    0.0    0.0    0.0    0.0    0.0
          JOINT   51                                    -996.8 111111


                   1         2         3         4         5         6         7         8
          12345678901234567890123456789012345678901234567890123456789012345678901234567890
```

A.8 Dynamic characteristics

```
DYNPAC INPUT
DYNOPT +ZMN 10CONS7.84905  1.025                  1.0         SA-Z
END

LDOPT       NF+Z1.0300007.850000 -41.600  42.720GLOBMN DYN      CMB   NP      K
    DYNAMIC CHARECTERISTICS OF PLATFORM
OPTIONS      MN       SDUC   3 3              PT
LCSEL ST        C005
SECT
*
SECT PILSTUB   PRI630.296508500.6508500.6508500. 10.0       10.0
GRUP
*
GRUP STB PILSTUB              20.508.00034.50 9    1.001.00     0.500F7.8490
MEMBER
*
PGRUP
*
PLATE
*
JOINT
*
JOINT 101  -15.073-18.000-41.285                      222000
JOINT 103    0.000-18.000-41.285                      222000
JOINT 104    0.000 18.000-41.285                      222000
JOINT 111    0.000-18.000-32.861                      222000
JOINT 112    0.000-18.000-16.566                      222000
JOINT 113    0.000-18.000 -1.397                      222000
JOINT 114    0.000 18.000-32.861                      222000
JOINT 115   -0.001 18.000-16.565                      222000
JOINT 116    0.000 18.000 -1.397                      222000
JOINT 119   15.073-18.000-41.285                      222000
JOINT 181  -15.073 18.000-41.285                      222000
JOINT 199   15.073 18.000-41.285                      222000
JOINT 201  -13.075-18.000-25.300                      222000
JOINT 219   13.075-18.000-25.300                      222000
JOINT 281  -13.075 18.000-25.300                      222000
JOINT 299   13.075 18.000-25.300                      222000
JOINT 301  -11.038-18.000 -9.000                      222000
JOINT 319   11.038-18.000 -9.000                      222000
JOINT 381  -11.038 18.000 -9.000                      222000
JOINT 399   11.038 18.000 -9.000                      222000
JOINT 401   -9.288-18.000  5.000                      222000
JOINT 419    9.288-18.000  5.000                      222000
JOINT 481   -9.288 18.000  5.000                      222000
JOINT 499    9.288 18.000  5.000                      222000
JOINT 4101  -9.000-18.000 13.300                      222000
JOINT 4120   9.000-18.000 13.300                      222000
JOINT 4501  -9.000 18.000 13.300                      222000
```

```
JOINT 4510   0.000 18.000 13.300                      222000
JOINT 4520   9.000 18.000 13.300                      222000
JOINT 5101  -9.000-18.000 19.900                      222000
JOINT 5110   0.000-18.000 19.900                      222000
JOINT 5120   9.000-18.000 19.900                      222000
JOINT 5501  -9.000 18.000 19.900                      222000
JOINT 5520   9.000 18.000 19.900                      222000
JOINT 6101  -9.000-18.000 27.900                      222000
JOINT 6110   0.000-18.000 27.900                      222000
JOINT 6120   9.000-18.000 27.900                      222000
JOINT 6501  -9.000 18.000 27.900                      222000
JOINT 6510   0.000 18.000 27.900                      222000
JOINT 6520   9.000 18.000 27.900                      222000
JOINT 7101  -9.000-18.000 35.500                      222000
JOINT 7110   0.000-18.000 35.500                      222000
JOINT 7120   9.000-18.000 35.500                      222000
JOINT 7501  -9.000 18.000 35.500                      222000
JOINT 7510   0.000 18.000 35.500                      222000
JOINT 7520   9.000 18.000 35.500                      222000
JOINT 8289 -16.473-18.000-52.482                      111111
JOINT 8290  16.473-18.000-52.482                      111111
JOINT 8291 -16.473 18.000-52.482                      111111
JOINT 8292  16.474 18.000-52.482                      111111
CDM
CDM     1.00 0.600       2.000       0.700       2.000
CDM   200.00 0.600       2.000       0.700       2.000
MGROV
MGROV   0.000     39.100   1.250 -41.6002.5400-4   1.400
MGROV   39.100    44.600   2.500 -41.6002.5400-4   1.400
MGROV   44.600    80.000         -41.6002.5400-4
GRPOV
*
MEMOV
*
LOAD
*
LCOMB
*
LCOMB C005 C0011.1500C0021.2000C0031.2000C0040.3500D0882.0000
END
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Appendix B Fatigue analysis results

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
8306	8306-8307	BLA	TUB	66.00	2.540	T	BRC	2.13		2.01	3.26	2.48	3.57	.0208066	R	2403.083
8306	1004-8306	BLA	TUB	66.00	2.540	T	CHD	2.13		4.70	5.15	3.29	6.77	.4704556	R	106.2799
1012	1012-1015	BLC	TUB	66.00	2.540	T	BRC	4.09		2.27	7.38	2.77	6.95	.0449812	L	1111.574
1012	1009-1012	BLB	TUB	86.40	3.000	T	CHD	4.09		4.12	11.13	3.46	11.04	.4361105	L	114.6498
399	399- 306	B2B	TUB	81.30	2.200	K	BRC	3.77	7.50	2.65	3.42	1.99	2.72	.0148306	T	3371.396
399	222- 399	L33	TUB	155.80	9.625	K	CHD	3.77		1.78	2.89	1.34	2.45	.0320710	R	1559.040
399	399-1211	B2D	TUB	81.30	2.000	TK	BRC	3.77	15.00	2.70	3.03	1.96	2.57	.0898829	R	556.2796
399	399-1009	L41	TUB	155.80	9.625	TK	CHD	3.77		2.04	2.53	1.23	2.20	.1755284	R	284.8542
399	399- 206	R2F	TUB	71.10	1.905	K	BRC	3.77	7.50	2.48	2.21	2.12	1.68	.1201366	T	416.1929
399	222- 399	L33	TUB	155.80	9.625	K	CHD	3.77		1.41	1.57	0.92	1.35	.0174618	TL	2863.395
399	399- 115	RBD	TUB	61.00	1.270	TK	BRC	3.77	15.00	2.49	2.44	1.79	1.72	.83188-2	TL	6010.515
399	222- 399	L33	TUB	155.80	9.625	TK	CHD	3.77		1.27	1.46	0.70	1.07	.33628-2	L	14868.40
399	399- 116	RBJ	TUB	50.80	1.905	TK	BRC	3.77	15.00	2.53	2.38	1.97	1.46	.64214-3	TL	77864.59
399	399-1009	L41	TUB	155.80	9.625	TK	CHD	3.77		1.81	1.79	0.80	1.09	.72245-3	L	69208.94

Azin Azarhoushang
Department of Civil Engineering

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
499	1203- 499	B3A	TUB	50.80	1.588	K	BRC	5.04	7.50	2.79	3.57	1.84	2.14	.0200030	R	2499.626
499	499- 599	LG5	TUB	154.78	8.750	K	CHD	5.04		1.49	2.60	0.97	1.54	.0225423	R	2218.048
499	499-1001	BLA	TUB	66.00	2.540	Y	BRC	5.04		2.68	5.04	2.12	2.96	.83279-2	L	6003.931
499	499- 599	LG5	TUB	154.78	8.750	Y	CHD	5.04		1.85	5.42	1.63	2.89	.0227458	L	2198.208
499	499-1010	BLA	TUB	66.00	2.540	T	BRC	5.04		2.65	4.61	2.11	3.10	.0528508	L	946.0603
499	499- 599	LG5	TUB	154.78	8.750	T	CHD	5.04		2.12	4.50	1.63	3.03	.1251028	L	399.6713
499	499- 125	RBF	TUB	50.20	2.240	K	BRC	5.04	7.50	2.82	3.43	2.03	2.05	.87041-2	R	5744.405
499	499- 599	LG5	TUB	154.78	8.750	K	CHD	5.04		2.06	3.09	1.20	1.76	.0161727	R	3091.624
319	319- 303	B2A	TUB	81.30	2.000	TK	BRC	3.31	15.00	2.83	3.15	2.06	2.80	.12377-2	BL	40396.76
319	319- 323	L45	TUB	154.78	8.750	TK	CHD	3.31		2.35	2.84	1.41	2.54	.15364-2	L	32544.56
319	319- 306	B2B	TUB	81.30	2.200	K	BRC	3.31	7.50	2.82	3.34	2.10	2.96	.0162211	B	3082.403
319	225- 319	L35	TUB	154.78	8.750	K	CHD	3.31		2.32	3.12	1.54	2.83	.0129603	B	3857.950
319	319- 206	R2E	TUB	71.10	1.905	K	BRC	3.31	7.50	2.40	2.21	2.22	2.00	.0951410	T	525.5360
319	225- 319	L35	TUB	154.78	8.750	K	CHD	3.31		1.63	1.80	1.06	1.71	.0268792	TL	1860.173

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
319	319- 112	RAD	TUB	61.00	1.270	TK	BRC	3.31	15.00	2.52	2.50	1.88	1.99	.58810-3	TL	85019.62
319	225- 319	L35	TUB	154.78	8.750	TK	CHD	3.31		1.55	1.70	0.82	1.31	.29537-3	L	169281.7
319	319- 113	RAH	TUB	50.80	1.905	TK	BRC	3.31	15.00	2.65	2.52	2.07	1.63	.83888-3	L	59603.21
319	319- 323	L45	TUB	154.78	8.750	TK	CHD	3.31		2.07	2.07	0.94	1.29	.11558-2	L	43260.02
381	381- 305	B2B	TUB	81.30	2.200	K	BRC	3.31	7.50	2.76	3.42	2.10	2.97	.0123889	B	4035.880
381	224- 381	L35	TUB	154.78	8.750	K	CHD	3.31		2.18	3.18	1.54	2.84	.92203-2	B	5422.842
381	381-8297	B2D	TUB	81.30	2.000	TK	BRC	3.31	15.00	2.88	3.06	2.06	2.78	.15081-2	BL	33153.56
381	381- 322	L45	TUB	154.78	8.750	TK	CHD	3.31		2.51	2.79	1.41	2.53	.18488-2	BL	27044.39
381	381- 205	R1F	TUB	71.10	1.905	K	BRC	3.31	7.50	2.44	2.22	2.22	1.92	.0949951	T	526.3430
381	224- 381	L35	TUB	154.78	8.750	K	CHD	3.31		1.60	1.79	1.06	1.64	.0242147	TR	2064.861
381	381- 115	RBE	TUB	61.00	1.270	TK	BRC	3.31	15.00	2.50	2.49	1.88	1.99	.29831-2	TR	16760.92
381	224- 381	L35	TUB	154.78	8.750	TK	CHD	3.31		1.62	1.73	0.82	1.32	.24669-2	R	20268.18
381	381- 116	RBH	TUB	50.80	1.905	TK	BRC	3.31	15.00	2.65	2.52	2.07	1.58	.10121-2	TR	49401.12
381	381- 322	L45	TUB	154.78	8.750	TK	CHD	3.31		2.06	2.06	0.94	1.25	.14808-2	R	33766.02

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
301	301- 303	B2A	TUB	81.30	2.000	TK	BRC	3.31	15.00	2.82	3.18	2.06	2.79	.15296-2	BR	32688.79
301	301- 324	L45	TUB	154.78	8.750	TK	CHD	3.31		2.31	2.86	1.41	2.53	.17659-2	BR	28313.94
301	301- 305	B2B	TUB	81.30	2.200	K	BRC	3.31	7.50	2.79	3.38	2.10	2.97	.0145335	B	3440.331
301	223- 301	L35	TUB	154.78	8.750	K	CHD	3.31		2.25	3.15	1.54	2.83	.0112494	B	4444.666
301	301- 205	R1E	TUB	71.10	1.905	K	BRC	3.31	7.50	2.42	2.21	2.22	1.97	.0922385	T	542.0732
301	223- 301	L35	TUB	154.78	8.750	K	CHD	3.31		1.62	1.79	1.06	1.68	.0249314	TR	2005.501
301	301- 112	RAE	TUB	61.00	1.270	TK	BRC	3.31	15.00	2.54	2.52	1.88	1.97	.63102-3	TR	79236.22
301	223- 301	L35	TUB	154.78	8.750	TK	CHD	3.31		1.52	1.70	0.82	1.30	.31682-3	R	157820.5
301	301- 113	RAJ	TUB	50.80	1.905	TK	BRC	3.31	15.00	2.62	2.49	2.08	1.61	.46924-3	R	106556.4
301	301- 324	L45	TUB	154.78	8.750	TK	CHD	3.31		2.04	2.04	0.93	1.28	.65498-3	R	76337.95
301	301-1103	RS1	TUB	25.40	1.270	T	BRC	3.31		3.21	2.85	1.58	1.26	.20858-2	R	23971.83
301	301- 324	L45	TUB	154.78	8.750	T	CHD	3.31		1.44	1.47	0.59	0.75	.79782-3	R	62671.01
304	305- 304	B2C	TUB	66.00	1.750	K	BRC	7.25	7.50	2.86	4.28	2.70	6.07	.57433-2	L	8705.756
304	8298- 304	B2A	TUB	81.30	2.540	K	CHD	7.25		4.63	6.28	2.66	8.86	.0659401	L	758.2636

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
304	306- 304	B2C	TUB	66.00	1.750	K	BRC	7.25	7.50	2.88	4.10	2.70	6.18	.56167-2	R	8901.995
304	1212- 304	B2A	TUB	81.30	2.540	K	CHD	7.25		4.59	6.01	2.66	9.03	.0646530	R	773.3595
206	203- 206	B1C	TUB	50.80	1.270	K	BRC	37.55	54.19	2.65	2.17	2.40	1.50	.80494-4	T	621165.6
206	206- 219	B1B	TUB	101.60	4.500	K	CHD	37.55		2.15	1.85	0.84	1.12	.16086-4	T	3108244.
206	204- 206	B1C	TUB	50.80	1.270	K	BRC	37.55	54.19	2.72	2.20	2.40	1.49	.46520-4	T	1074816.
206	206- 299	B1B	TUB	101.60	4.500	K	CHD	37.55		2.21	1.89	0.84	1.12	.14903-4	R	3354921.
206	106- 206	R2A	TUB	45.70	1.270	TK	BRC	37.55	15.00	3.03	3.29	2.07	3.92	.14914-2	T	33526.58
206	206- 219	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.40	2.73	1.20	2.86	.45604-3	T	109639.7
206	206- 306	R2B	TUB	45.70	1.270	TK	BRC	37.55	15.00	3.02	3.33	2.07	3.92	.55331-2	B	9036.481
206	206- 219	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.37	2.76	1.20	2.86	.17380-2	B	28768.48
206	119- 206	R2C	TUB	71.10	1.900	TK	BRC	37.55	15.00	2.13	2.25	2.49	2.45	.0231812	T	2156.919
206	206- 219	B1B	TUB	101.60	4.500	TK	CHD	37.55		1.99	2.59	1.31	2.56	.0302683	T	1651.892
206	199- 206	R2D	TUB	71.10	1.900	TK	BRC	37.55	15.00	2.09	2.16	2.49	2.50	.0217892	T	2294.715
206	206- 299	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.05	2.45	1.31	2.60	.0291524	T	1715.124

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
206	319- 206	R2E	TUB	71.10	1.905	TK	BRC	37.55	15.00	2.08	2.16	2.48	2.59	.0234044	T	2136.349
206	206- 219	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.08	2.44	1.32	2.70	.0612509	T	816.3148
206	399- 206	R2F	TUB	71.10	1.905	TK	BRC	37.55	15.00	2.13	2.24	2.48	2.55	.0222274	T	2249.475
206	206- 299	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.05	2.57	1.32	2.66	.0612970	TL	815.7002
205	203- 205	B1C	TUB	50.80	1.270	K	BRC	37.55	54.19	2.59	2.14	2.40	1.50	.48340-4	T	1034344.
205	205- 201	B1B	TUB	101.60	4.500	K	CHD	37.55		2.10	1.82	0.84	1.13	.13454-4	L	3716419.
205	204- 205	B1C	TUB	50.80	1.270	K	BRC	37.55	54.19	2.69	2.19	2.40	1.50	.26742-4	BR	1869704.
205	205- 281	B1B	TUB	101.60	4.500	K	CHD	37.55		2.19	1.88	0.84	1.12	.15920-4	L	3140753.
205	105- 205	R1A	TUB	45.70	1.270	TK	BRC	37.55	15.00	3.04	3.27	2.07	3.93	.13200-2	T	37877.48
205	205- 201	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.42	2.71	1.20	2.87	.40362-3	T	123878.2
205	205- 305	R1B	TUB	45.70	1.270	TK	BRC	37.55	15.00	3.02	3.30	2.07	3.93	.47135-2	B	10607.80
205	205- 201	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.39	2.74	1.20	2.87	.14628-2	B	34180.78
205	101- 205	R1C	TUB	71.10	1.900	TK	BRC	37.55	15.00	2.10	2.20	2.49	2.48	.0201546	T	2480.821
205	205- 201	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.02	2.50	1.31	2.58	.0271262	T	1843.238

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
205	181- 205	R1D	TUB	71.10	1.900	TK	BRC	37.55	15.00	2.11	2.18	2.49	2.49	.0199224	T	2509.740
205	205- 281	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.08	2.48	1.31	2.60	.0269833	T	1853.000
205	301- 205	R1E	TUB	71.10	1.905	TK	BRC	37.55	15.00	2.09	2.16	2.48	2.59	.0203653	T	2455.161
205	205- 201	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.09	2.45	1.32	2.71	.0551021	TR	907.4071
205	381- 205	R1F	TUB	71.10	1.905	TK	BRC	37.55	15.00	2.11	2.20	2.48	2.58	.0212644	T	2351.344
205	205- 281	B1B	TUB	101.60	4.500	TK	CHD	37.55		2.10	2.51	1.32	2.69	.0578244	TR	864.6873
305	305- 303	B2C	TUB	66.00	1.750	K	BRC	34.45	7.50	3.39	2.20	2.88	2.95	.10647-2	T	46961.89
305	301- 305	B2B	TUB	81.30	2.540	K	CHD	34.45		4.72	4.03	1.87	4.30	.45722-2	TR	10935.55
305	305- 304	B2C	TUB	66.00	1.750	K	BRC	34.45	7.50	4.10	2.37	2.88	2.87	.58705-3	BR	85171.09
305	381- 305	B2B	TUB	81.30	2.540	K	CHD	34.45		5.68	4.68	1.87	4.19	.35547-2	R	14065.94
305	205- 305	R1B	TUB	45.70	1.270	T	BRC	34.45		5.19	9.15	2.71	6.32	.0216032	L	2314.475
305	301- 305	B2B	TUB	81.30	2.540	T	CHD	34.45		9.84	8.25	2.51	6.81	.0394538	L	1267.307
306	306- 303	B2C	TUB	66.00	1.750	K	BRC	34.45	7.50	4.02	2.36	2.88	2.88	.18127-2	T	27583.33
306	319- 306	B2B	TUB	81.30	2.540	K	CHD	34.45		5.58	4.61	1.87	4.20	.40627-2	TL	12307.23

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
306	306- 304	B2C	TUB	66.00	1.750	K	BRC	34.45	7.50	4.35	2.43	2.88	2.84	.11660-2	T	42881.60
306	399- 306	B2B	TUB	81.30	2.540	K	CHD	34.45		6.02	4.90	1.87	4.15	.19790-2	R	25264.93
306	206- 306	R2B	TUB	45.70	1.270	T	BRC	34.45		5.19	9.15	2.71	6.32	.0209017	R	2392.153
306	319- 306	B2B	TUB	81.30	2.540	T	CHD	34.45		9.83	8.25	2.51	6.81	.0382428	R	1307.435
303	305- 303	B2C	TUB	66.00	1.750	K	BRC	20.51	7.50	3.95	4.19	2.70	6.30	.26420-2	R	18924.75
303	301- 303	B2A	TUB	81.30	2.540	K	CHD	20.51		6.81	6.63	2.66	9.20	.0323021	R	1547.888
303	306- 303	B2C	TUB	66.00	1.750	K	BRC	20.51	7.50	3.86	4.08	2.70	6.35	.22967-2	L	21770.54
303	319- 303	B2A	TUB	81.30	2.540	K	CHD	20.51		6.59	6.43	2.66	9.28	.0277261	L	1803.357
116	381- 116	RBH	TUB	50.80	2.540	Y	BRC	12.73		3.64	2.58	2.41	1.47	.52264-3	B	95667.95
116	126- 116	RBG	TUB	50.80	2.540	Y	CHD	12.73		5.59	3.55	2.90	2.75	.16636-2	R	30055.62
116	125- 116	RBK	TUB	50.80	2.540	Y	BRC	12.73		3.64	3.44	2.70	2.17	.21938-2	T	22791.79
116	399- 116	RBJ	TUB	50.80	1.905	Y	CHD	12.73		7.37	6.43	4.08	4.82	.0229614	R	2177.566
199	199- 104	B0A	TUB	61.00	1.905	K	BRC	17.43	7.50	3.01	3.94	1.97	2.71	.44435-4	T	1125230.

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
199	199- 299	LG2	TUB	154.78	8.750	K	CHD	17.43		2.43	2.92	1.23	2.23	.19485-4	T	2566049.
199	199- 121	B0B	TUB	61.00	1.905	K	BRC	17.43	7.50	3.05	3.99	1.97	2.79	.57105-4	T	875577.8
199	199- 299	LG2	TUB	154.78	8.750	K	CHD	17.43		2.49	2.97	1.24	2.29	.25556-4	T	1956452.
199	199- 206	R2D	TUB	71.10	1.900	K	BRC	17.43	7.50	2.93	2.81	2.22	1.88	.79537-2	BL	6286.364
199	199- 299	LG2	TUB	154.78	8.750	K	CHD	17.43		2.25	2.37	1.06	1.60	.0128249	L	3898.656
199	199- 114	RBC	TUB	66.00	1.430	K	BRC	17.43	7.50	2.88	2.92	2.01	1.82	.0223676	T	2235.375
199	199- 299	LG2	TUB	154.78	8.750	K	CHD	17.43		1.75	1.91	0.87	1.30	.73348-2	T	6816.807
181	181- 104	B0A	TUB	61.00	1.905	K	BRC	17.43	7.50	3.00	3.87	1.97	2.72	.42020-4	T	1189896.
181	181- 281	LG2	TUB	154.78	8.750	K	CHD	17.43		2.43	2.88	1.23	2.24	.18016-4	T	2775348.
181	181- 118	B0B	TUB	61.00	1.905	K	BRC	17.43	7.50	3.05	3.89	1.97	2.82	.49268-4	T	1014856.
181	181- 281	LG2	TUB	154.78	8.750	K	CHD	17.43		2.49	2.92	1.24	2.31	.21918-4	T	2281185.
181	181- 205	R1D	TUB	71.10	1.900	K	BRC	17.43	7.50	2.93	2.81	2.22	1.88	.76306-2	BR	6552.528
181	181- 281	LG2	TUB	154.78	8.750	K	CHD	17.43		2.25	2.36	1.06	1.60	.0123770	R	4039.740
181	181- 114	RBB	TUB	66.00	1.430	K	BRC	17.43	7.50	2.85	2.90	2.01	1.84	.0221876	T	2253.511

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
181	181- 281	LG2	TUB	154.78	8.750	K	CHD	17.43		1.74	1.89	0.87	1.32	.72550-2	T	6891.843
1001	499-1001	BLA	TUB	66.00	2.540	T	BRC	2.40		1.92	6.02	2.77	5.85	.23914-2	BL	20908.38
1001	1005-1001	BLD	TUB	86.40	3.000	T	CHD	2.40		3.24	9.49	3.46	9.28	.0192633	BL	2595.608
299	206- 299	B1B	TUB	61.00	1.270	T	BRC	17.76		2.95	3.92	1.82	2.20	.83176-2	B	6011.331
299	299- 221	L32	TUB	154.78	8.750	T	CHD	17.76		1.67	2.08	0.88	1.45	.18322-2	B	27289.81
299	299-1223	B1D	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.40	2.43	1.83	2.58	.10782-2	R	46375.08
299	299- 221	L32	TUB	154.78	8.750	TK	CHD	17.76		1.59	1.60	0.87	1.70	.73968-3	R	67596.82
299	299- 115	RBE	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.13	2.12	1.98	1.63	.11782-2	BL	42438.84
299	299- 221	L32	TUB	154.78	8.750	TK	CHD	17.76		1.51	1.51	0.73	1.07	.11454-2	BL	43651.30
299	299- 114	RBM	TUB	66.00	1.270	TK	BRC	17.76	15.00	2.58	2.74	1.88	2.16	.0165567	L	3019.929
299	199- 299	LG2	TUB	154.78	8.750	TK	CHD	17.76		1.76	1.85	0.86	1.45	.0123757	L	4040.191
481	481-8293	B3A	TUB	50.80	1.588	K	BRC	13.56	7.50	2.81	3.24	1.84	2.40	.0160864	R	3108.210
481	481- 581	LG5	TUB	154.78	8.750	K	CHD	13.56		1.86	2.13	0.97	1.72	.0161236	R	3101.044

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
481	481- 126	RBF	TUB	50.20	2.240	K	BRC	13.56	7.50	2.96	3.40	2.03	2.19	.20275-2	BL	24661.19
481	481- 581	LG5	TUB	154.78	8.750	K	CHD	13.56		2.48	2.81	1.20	1.89	.26644-2	L	18765.99
8307	8306-8307	BLA	TUB	66.00	2.540	Y	BRC	7.76		4.40	1.47	3.23	0.80	.0160111	T	3122.836
8307	1004-8307	BLA	TUB	66.00	2.540	Y	CHD	7.76		7.24	1.01	1.55	1.52	.91980-2	T	5435.961
113	301- 113	RAJ	TUB	50.80	2.540	Y	BRC	13.28		4.28	2.65	2.41	1.67	.15048-3	B	332279.5
113	124- 113	RAF	TUB	50.80	2.540	Y	CHD	13.28		7.36	3.61	2.90	3.13	.66908-3	L	74729.17
113	123- 113	RAK	TUB	50.80	2.540	Y	BRC	13.28		4.58	3.52	2.70	2.51	.70473-3	T	70949.45
113	319- 113	RAH	TUB	50.80	1.905	Y	CHD	13.28		10.01	6.51	4.08	5.56	.0148695	L	3362.586
119	119- 103	B0A	TUB	61.00	1.905	K	BRC	17.43	7.50	3.01	4.02	1.97	2.70	.10428-4	T	4794796.
119	119- 219	LG2	TUB	154.78	8.750	K	CHD	17.43		2.44	2.97	1.23	2.21	.46939-5	T	10652.+3
119	119- 122	B0B	TUB	61.00	1.905	K	BRC	17.43	7.50	3.06	3.57	1.97	2.90	.50279-4	T	994445.1
119	119- 219	LG2	TUB	154.78	8.750	K	CHD	17.43		2.49	2.75	1.24	2.38	.21455-4	T	2330420.
119	119- 206	R2C	TUB	71.10	1.900	K	BRC	17.43	7.50	2.91	2.79	2.22	1.90	.89042-2	BL	5615.345

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
119	119- 219	LG2	TUB	154.78	8.750	K	CHD	17.43		2.24	2.35	1.06	1.62	.0144984	L	3448.651
119	119- 111	RAC	TUB	66.00	1.430	K	BRC	17.43	7.50	2.86	2.90	2.01	1.84	.49510-2	T	10098.92
119	119- 219	LG2	TUB	154.78	8.750	K	CHD	17.43		1.74	1.90	0.87	1.32	.15547-2	T	32160.24
101	101- 103	B0A	TUB	61.00	1.905	K	BRC	17.43	7.50	3.00	3.86	1.97	2.73	.97178-5	T	5145214.
101	101- 201	LG2	TUB	154.78	8.750	K	CHD	17.43		2.43	2.87	1.23	2.24	.42176-5	T	11855.+3
101	101- 117	B0B	TUB	61.00	1.905	K	BRC	17.43	7.50	3.06	3.69	1.97	2.87	.44778-4	T	1116613.
101	101- 201	LG2	TUB	154.78	8.750	K	CHD	17.43		2.49	2.82	1.24	2.36	.19296-4	T	2591183.
101	101- 205	R1C	TUB	71.10	1.900	K	BRC	17.43	7.50	2.92	2.81	2.22	1.89	.79993-2	BR	6250.553
101	101- 201	LG2	TUB	154.78	8.750	K	CHD	17.43		2.25	2.36	1.06	1.60	.0131641	R	3798.205
101	101- 111	RAB	TUB	66.00	1.430	K	BRC	17.43	7.50	2.84	2.88	2.01	1.86	.48039-2	T	10408.13
101	101- 201	LG2	TUB	154.78	8.750	K	CHD	17.43		1.73	1.88	0.87	1.33	.15020-2	T	33288.79
101	101-1101	RS1	TUB	25.40	1.270	T	BRC	17.43		3.32	3.36	1.58	1.28	.30897-8	R	16183.+6
101	101- 201	LG2	TUB	154.78	8.750	T	CHD	17.43		1.71	1.57	0.59	0.76	.11146-8	R	44859.+6
1010	499-1010	BLA	TUB	66.00	2.540	T	BRC	2.40		1.92	6.02	2.77	5.85	.17493-2	BR	28582.51

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
1010	1017-1010	BLD	TUB	86.40	3.000	T	CHD	2.40		3.24	9.49	3.46	9.28	.0117399	BR	4258.981
281	205- 281	B1B	TUB	61.00	1.270	T	BRC	17.76		2.95	3.92	1.82	2.20	.55426-2	B	9020.958
281	281- 227	L34	TUB	154.78	8.750	T	CHD	17.76		1.67	2.08	0.88	1.45	.12045-2	BR	41510.59
281	281-8303	B1D	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.42	2.45	1.83	2.53	.55821-3	L	89571.61
281	281- 227	L34	TUB	154.78	8.750	TK	CHD	17.76		1.60	1.61	0.87	1.67	.38501-3	L	129865.3
281	281- 115	RBD	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.11	2.10	1.98	1.65	.14967-2	BR	33407.66
281	281- 227	L34	TUB	154.78	8.750	TK	CHD	17.76		1.49	1.49	0.73	1.09	.14577-2	BR	34300.44
281	281- 114	RBL	TUB	66.00	1.270	TK	BRC	17.76	15.00	2.60	2.75	1.88	2.14	.0105997	R	4717.104
281	181- 281	LG2	TUB	154.78	8.750	TK	CHD	17.76		1.78	1.87	0.86	1.44	.80290-2	R	6227.449
115	299- 115	RBE	TUB	61.00	1.270	Y	BRC	26.95		2.39	2.62	2.30	1.26	.29219-2	R	17111.87
115	399- 115	RBD	TUB	61.00	2.060	Y	CHD	26.95		2.26	3.06	2.14	1.85	.97900-2	R	5107.261
115	381- 115	RBE	TUB	61.00	1.270	Y	BRC	26.95		2.47	2.63	2.30	1.29	.28671-2	R	17439.04
115	281- 115	RBD	TUB	61.00	2.060	Y	CHD	26.95		2.46	3.06	2.14	1.89	.98463-2	R	5078.053
1002	8306-1002	BLA	TUB	66.00	2.540	T	BRC	5.60		2.59	7.60	2.77	7.23	.69400-3	L	72046.55

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1002	1002-1005	BLD	TUB	86.40	3.000	T	CHD	5.60		4.91	11.17	3.46	11.47	.88748-2	L	5633.905
1006	1006-1018	BLE	TUB	86.40	3.200	T	BRC	6.00		3.02	3.71	2.49	4.62	.83134-3	BL	60143.58
1006	1005-1006	BLE	TUB	86.40	3.200	T	CHD	6.00		7.35	5.66	3.34	8.78	.87556-2	BL	5710.624
114	104- 114	RBA	TUB	45.72	1.588	K	BRC	30.29	7.50	2.95	4.57	2.63	5.04	.24657-3	T	202782.5
114	181- 114	RBB	TUB	66.00	2.540	K	CHD	30.29		3.40	6.60	2.39	6.51	.50220-3	R	99561.42
114	199- 114	RBC	TUB	66.00	1.430	K	BRC	30.29	7.50	2.37	2.08	2.26	0.91	.50674-2	B	9867.066
114	299- 114	RBM	TUB	66.00	2.540	K	CHD	30.29		1.81	2.10	1.78	1.27	.29928-2	BR	16706.71
114	281- 114	RBL	TUB	66.00	1.270	Y	BRC	30.29		2.49	2.05	2.20	0.88	.59882-2	T	8349.772
114	181- 114	RBB	TUB	66.00	2.540	Y	CHD	30.29		1.88	1.89	1.62	1.15	.30347-2	R	16475.83
1015	1012-1015	BLC	TUB	66.00	2.540	Y	BRC	8.59		3.22	2.58	3.15	2.54	.56179-2	T	8900.059
1015	1009-1015	BLB	TUB	86.40	3.000	Y	CHD	8.59		5.25	4.93	2.19	4.03	.35757-2	T	13983.33
201	201- 203	B1A	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.42	2.46	1.83	2.56	.21005-3	BR	238033.2

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
201	201- 228	L34	TUB	154.78	8.750	TK	CHD	17.76		1.59	1.61	0.87	1.69	.88035-4	R	567953.8
201	205- 201	B1B	TUB	61.00	1.270	T	BRC	17.76		2.95	3.92	1.82	2.20	.51150-2	BR	9775.189
201	201- 228	L34	TUB	154.78	8.750	T	CHD	17.76		1.67	2.08	0.88	1.45	.11902-2	BR	42009.35
201	201- 112	RAD	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.13	2.11	1.98	1.64	.21129-3	B	236637.1
201	201- 228	L34	TUB	154.78	8.750	TK	CHD	17.76		1.50	1.49	0.73	1.08	.17980-3	B	278084.8
201	201- 111	RAM	TUB	66.00	1.270	TK	BRC	17.76	15.00	2.59	2.74	1.88	2.17	.27309-2	R	18309.04
201	101- 201	LG2	TUB	154.78	8.750	TK	CHD	17.76		1.77	1.86	0.86	1.46	.18498-2	R	27029.68
201	201-1102	RS1	TUB	25.40	1.270	T	BRC	17.76		3.32	3.36	1.58	1.28	.24159-5	R	20696.+3
201	201- 228	L34	TUB	154.78	8.750	T	CHD	17.76		1.71	1.57	0.59	0.76	.86986-6	R	57481.+3
1011	8307-1011	BLA	TUB	66.00	2.540	T	BRC	5.60		2.59	7.60	2.77	7.23	.43292-3	BL	115494.2
1011	1011-1017	BLD	TUB	86.40	3.000	T	CHD	5.60		4.91	11.17	3.46	11.47	.48779-2	L	10250.24
219	219- 203	B1A	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.41	2.44	1.83	2.57	.24208-3	BL	206542.7
219	219- 226	L34	TUB	154.78	8.750	TK	CHD	17.76		1.59	1.61	0.87	1.70	.11539-3	L	433327.9
219	206- 219	B1B	TUB	61.00	1.270	T	BRC	17.76		2.95	3.92	1.82	2.20	.48501-2	B	10309.01

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JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
219	219- 226	L34	TUB	154.78	8.750	T	CHD	17.76		1.67	2.08	0.88	1.45	.10938-2	BL	45712.18
219	219- 112	RAE	TUB	61.00	1.270	TK	BRC	17.76	15.00	2.13	2.11	1.98	1.66	.24057-3	B	207836.8
219	219- 226	L34	TUB	154.78	8.750	TK	CHD	17.76		1.51	1.50	0.73	1.09	.20214-3	B	247351.9
219	219- 111	RAL	TUB	66.00	1.270	TK	BRC	17.76	15.00	2.59	2.76	1.88	2.16	.22981-2	L	21757.49
219	119- 219	LG2	TUB	154.78	8.750	TK	CHD	17.76		1.76	1.86	0.86	1.45	.16186-2	L	30890.21
1029	1029-1034	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.58445-3	L	85550.56
1029	1028-1029	BLF	TUB	86.40	3.000	T	CHD	2.67		2.67	8.80	2.88	6.87	.28716-2	L	17412.04
1025	1025-1030	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.53669-3	L	93163.30
1025	1022-1025	BLF	TUB	86.40	3.000	T	CHD	2.67		2.67	8.80	2.88	6.87	.26873-2	L	18606.03
401	401- 419	B3A	TUB	50.80	1.588	K	BRC	13.56	7.50	2.88	3.55	1.84	2.28	.18807-5	T	26586.+3
401	401- 501	LG5	TUB	154.78	8.750	K	CHD	13.56		1.87	2.27	0.97	1.63	.87351-6	L	57240.+3
401	401- 124	RAG	TUB	50.20	2.240	K	BRC	13.56	7.50	3.00	3.56	2.03	2.13	.15264-2	BR	32757.76
401	401- 501	LG5	TUB	154.78	8.750	K	CHD	13.56		2.55	2.96	1.20	1.84	.21690-2	R	23051.76

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
1024	1034-1024	BLG	TUB	86.40	3.000	T	BRC	5.30		2.76	3.60	2.46	4.49	.87198-4	L	573406.4
1024	1023-1024	BLE	TUB	86.40	3.200	T	CHD	5.30		6.36	5.27	3.16	8.23	.18879-2	L	26484.88
419	401- 419	B3A	TUB	50.80	1.588	K	BRC	13.56	7.50	2.86	3.45	1.84	2.32	.22790-5	R	21940.+3
419	419- 519	LG5	TUB	154.78	8.750	K	CHD	13.56		1.87	2.22	0.97	1.66	.15304-5	R	32671.+3
419	419- 123	RAG	TUB	50.20	2.240	K	BRC	13.56	7.50	2.99	3.54	2.03	2.14	.11591-2	R	43136.05
419	419- 519	LG5	TUB	154.78	8.750	K	CHD	13.56		2.54	2.94	1.20	1.84	.17242-2	R	28998.54
419	1224- 419	SEA	TUB	27.30	1.270	Y	BRC	13.56		3.26	3.29	1.58	1.27	.92485-9	B	54063.+6
419	419- 519	LG5	TUB	154.78	8.750	Y	CHD	13.56		1.62	1.56	0.59	0.76	.4036-10	B	12388.+8
1016	1024-1016	BLE	TUB	86.40	3.200	T	BRC	6.00		3.02	3.71	2.49	4.62	.14348-3	BR	348484.2
1016	1016-1017	BLE	TUB	86.40	3.200	T	CHD	6.00		7.35	5.66	3.34	8.78	.16735-2	BR	29877.12
111	103- 111	RAA	TUB	45.72	1.588	K	BRC	30.29	7.50	2.85	4.86	2.63	4.95	.62624-4	L	798417.3
111	101- 111	RAB	TUB	66.00	2.540	K	CHD	30.29		3.14	7.11	2.39	6.40	.45082-3	L	110909.4
111	119- 111	RAC	TUB	66.00	1.430	K	BRC	30.29	7.50	2.43	2.08	2.26	0.94	.11429-2	B	43746.46

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
111	219- 111	RAL	TUB	66.00	2.540	K	CHD	30.29		1.95	2.11	1.78	1.30	.64669-3	BL	77316.82
111	201- 111	RAM	TUB	66.00	1.270	Y	BRC	30.29		2.49	2.05	2.20	0.88	.13756-2	T	36348.18
111	101- 111	RAB	TUB	66.00	2.540	Y	CHD	30.29		1.88	1.89	1.62	1.15	.57091-3	L	87578.98
112	219- 112	RAE	TUB	61.00	1.270	Y	BRC	26.95		2.56	2.64	2.30	1.32	.42217-3	L	118434.6
112	319- 112	RAD	TUB	61.00	2.060	Y	CHD	26.95		2.69	3.06	2.14	1.93	.13652-2	L	36623.84
112	301- 112	RAE	TUB	61.00	1.270	Y	BRC	26.95		2.51	2.64	2.30	1.30	.45769-3	TL	109244.2
112	201- 112	RAD	TUB	61.00	2.060	Y	CHD	26.95		2.56	3.06	2.14	1.91	.13279-2	L	37652.21
1007	1012-1007	BLB	TUB	86.40	3.000	T	BRC	11.00		4.49	3.77	2.46	4.49	.61586-4	R	811870.0
1007	1022-1007	BLE	TUB	86.40	3.200	T	CHD	11.00		10.69	5.27	3.16	8.23	.12130-2	R	41219.38
1026	1026-1031	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.24317-3	L	205613.8
1026	1025-1026	BLF	TUB	86.40	3.000	T	CHD	2.67		2.67	8.80	2.88	6.87	.12079-2	L	41394.72
1034	1029-1034	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.22084-3	R	226408.1

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
1034	1033-1034	BLG	TUB	86.40	3.000	T	CHD	2.67		2.67	8.80	2.88	6.87	.10901-2	R	45866.20
1028	1028-1033	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.20273-3	L	246637.2
1028	1027-1028	BLF	TUB	86.40	3.000	T	CHD	2.67		2.67	8.80	2.88	6.87	.98998-3	L	50506.13
203	203- 205	B1C	TUB	50.80	1.270	K	BRC	24.59	7.50	3.88	3.27	2.58	5.15	.44429-3	T	112538.3
203	201- 203	B1A	TUB	61.00	2.060	K	CHD	24.59		6.32	5.38	2.23	7.12	.93598-3	T	53419.96
203	203- 206	B1C	TUB	50.80	1.270	K	BRC	24.59	7.50	3.93	3.29	2.58	5.14	.37318-3	T	133982.4
203	219- 203	B1A	TUB	61.00	2.060	K	CHD	24.59		6.43	5.44	2.23	7.10	.76504-3	T	65356.07
1027	1027-1032	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.16317-3	L	306435.5
1027	1026-1027	BLF	TUB	86.40	3.000	T	CHD	2.67		2.67	8.79	2.88	6.87	.79840-3	L	62624.95
106	106- 206	R2A	TUB	45.70	1.270	T	BRC	6.18		2.96	5.59	2.32	4.82	.48049-3	T	104060.4
106	121- 106	B0D	TUB	61.00	2.540	T	CHD	6.18		3.75	5.34	2.04	5.66	.79554-3	L	62850.07
104	118- 104	B0C	TUB	61.00	1.270	K	BRC	28.58	7.50	5.21	2.01	2.27	1.99	.17640-5	T	28345.+3

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JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
104	181- 104	B0A	TUB	61.00	2.540	K	CHD	28.58		7.95	1.77	1.40	2.58	.10206-5	T	48989.+3
104	121- 104	B0C	TUB	61.00	1.270	K	BRC	28.58	7.50	5.61	2.04	2.27	1.96	.14247-5	T	35095.+3
104	199- 104	B0A	TUB	61.00	2.540	K	CHD	28.58		8.62	1.74	1.40	2.54	.96922-6	T	51588.+3
104	104- 114	RBA	TUB	45.72	1.588	T	BRC	28.58		7.94	6.91	2.44	5.34	.33541-3	B	149069.9
104	181- 104	B0A	TUB	61.00	2.540	T	CHD	28.58		16.74	6.82	2.47	7.08	.70577-3	B	70844.47
105	105- 205	R1A	TUB	45.70	1.270	T	BRC	6.18		2.96	5.59	2.32	4.82	.42697-3	B	117103.4
105	117- 105	B0D	TUB	61.00	2.540	T	CHD	6.18		3.75	5.34	2.04	5.66	.63455-3	L	78796.57
1030	1025-1030	BLH	TUB	45.72	1.905	T	BRC	2.67		2.25	7.46	2.77	5.63	.13262-4	R	3770172.
1030	1021-1030	BLG	TUB	86.40	3.000	T	CHD	2.67		2.41	10.07	2.88	6.73	.74361-4	R	672396.2
1030	1030-1035	BLI	TUB	45.72	1.905	T	BRC	2.67		2.31	8.40	2.77	5.46	.11764-3	L	425036.9
1030	1021-1030	BLG	TUB	86.40	3.000	T	CHD	2.67		2.03	11.90	2.88	6.53	.60320-3	L	82891.88
1033	1028-1033	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.73350-4	R	681666.9
1033	1032-1033	BLG	TUB	86.40	3.000	T	CHD	2.67		2.67	8.80	2.88	6.87	.36033-3	R	138759.8

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
1021	1021-1030	BLG	TUB	86.40	3.000	T	BRC	4.63		2.56	3.57	2.46	4.37	.15501-4	R	3225520.
1021	1018-1021	BLE	TUB	86.40	3.200	T	CHD	4.63		5.85	5.27	3.16	8.01	.35041-3	R	142689.2
103	117- 103	B0C	TUB	61.00	1.270	K	BRC	28.58	7.50	4.82	1.97	2.27	2.02	.17370-5	T	28786.+3
103	101- 103	B0A	TUB	61.00	2.540	K	CHD	28.58		7.29	1.80	1.40	2.63	.11624-5	T	43016.+3
103	122- 103	B0C	TUB	61.00	1.270	K	BRC	28.58	7.50	5.42	2.03	2.27	1.97	.19881-5	T	25150.+3
103	119- 103	B0A	TUB	61.00	2.540	K	CHD	28.58		8.31	1.76	1.40	2.56	.11028-5	T	45339.+3
103	103- 111	RAA	TUB	45.72	1.588	T	BRC	28.58		7.94	6.91	2.44	5.34	.83980-4	B	595382.6
103	101- 103	B0A	TUB	61.00	2.540	T	CHD	28.58		16.74	6.82	2.47	7.08	.17559-3	T	284756.1
1022	1022-1025	BLF	TUB	86.40	3.000	T	BRC	8.40		3.70	3.71	2.46	4.49	.19597-4	TR	2551431.
1022	1021-1022	BLE	TUB	86.40	3.200	T	CHD	8.40		8.71	5.27	3.16	8.23	.16425-3	TR	304419.8
1031	1026-1031	BLH	TUB	45.72	1.905	T	BRC	2.67		2.27	7.76	2.77	5.57	.19061-4	R	2623122.
1031	1030-1031	BLG	TUB	86.40	3.000	T	CHD	2.67		2.29	10.66	2.88	6.67	.10171-3	R	491575.3
1031	1031-1036	BLI	TUB	45.72	1.905	T	BRC	2.67		2.30	8.14	2.77	5.51	.29764-4	R	1679857.

JOINT	MEMBER	GRUP ID	TYPE ID	ORIGINAL OD (CM)	WT (CM)	JNT TYP	MEM TYP	CHORD LEN. (M)	GAP (CM)	* STRESS CONC. FACTORS * AX-CR	AX-SD	IN-PL	OU-PL	FATIGUE RESULTS DAMAGE	LOC	SVC LIFE
1031	1030-1031	BLG	TUB	86.40	3.000	T	CHD	2.67		2.14	11.39	2.88	6.59	.15153-3	R	329975.2
1032	1027-1032	BLH	TUB	45.72	1.905	T	BRC	2.67		2.21	6.80	2.77	5.75	.26967-4	R	1854094.
1032	1031-1032	BLG	TUB	86.40	3.000	T	CHD	2.67		2.67	8.79	2.88	6.87	.13348-3	R	374587.8
1013	1015-1013	BLB	TUB	86.40	3.000	T	BRC	11.00		4.49	3.77	2.46	4.49	.39509-5	L	12655.+3
1013	1013-1023	BLE	TUB	86.40	3.200	T	CHD	11.00		10.69	5.27	3.16	8.23	.78912-4	L	633617.9
1023	1029-1023	BLF	TUB	86.40	3.000	T	BRC	8.40		3.70	3.71	2.46	4.49	.45161-5	B	11071.+3
1023	1013-1023	BLE	TUB	86.40	3.200	T	CHD	8.40		8.71	5.27	3.16	8.23	.40406-4	BL	1237429.
1005	1005-1006	BLE	TUB	86.40	3.200	T	BRC	4.00		2.32	3.83	2.57	4.72	.12380-6	L	40387.+4
1005	1005-1001	BLD	TUB	86.40	3.000	T	CHD	4.00		6.19	6.45	3.60	9.30	.15144-5	L	33016.+3
121	121- 104	B0C	TUB	61.00	1.270	Y	BRC	17.22		5.73	2.12	2.27	1.73	.37459-6	T	13348.+4
121	199- 121	B0B	TUB	61.00	2.540	Y	CHD	17.22		8.61	1.46	1.40	2.24	.20583-6	T	24291.+4
1017	1016-1017	BLE	TUB	86.40	3.200	T	BRC	4.00		2.32	3.83	2.57	4.72	.17587-7	L	28431.+5

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1017	1017-1010	BLD	TUB	86.40	3.000	T	CHD	4.00		6.19	6.45	3.60	9.30	.21513-6	L	23241.+4
117	117- 103	B0C	TUB	61.00	1.270	Y	BRC	17.22		5.73	2.12	2.27	1.73	.13604-6	T	36755.+4
117	101- 117	B0B	TUB	61.00	2.540	Y	CHD	17.22		8.61	1.46	1.40	2.24	.20486-6	TL	24407.+4
122	122- 103	B0C	TUB	61.00	1.270	Y	BRC	17.22		5.73	2.12	2.27	1.73	.88097-7	T	56756.+4
122	119- 122	B0B	TUB	61.00	2.540	Y	CHD	17.22		8.61	1.46	1.40	2.24	.15280-6	TR	32722.+4
118	118- 104	B0C	TUB	61.00	1.270	Y	BRC	17.22		5.73	2.12	2.27	1.73	.59977-7	T	83366.+4
118	181- 118	B0B	TUB	61.00	2.540	Y	CHD	17.22		8.61	1.46	1.40	2.24	.85696-7	TR	58346.+4