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부유식 해양구조물의 신뢰성해석

- 설계변수의 불확실성 변화에 대한 구조시스템 신뢰성 -

Reliability Analysis of Floating Offshore Structures

- structural systems reliability to change in uncertainty of design variables -

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ABSTRACT

This paper is concerned with the the influence of changes in stochastic parameters of the important resistance variables such as the strength modelling parameter and material and geometric properties, on the system safety level of TLP structures. The effect of parameters governing the post-ultimate behaviour is also addressed. An extended incremental load method is employed for the present study, which has been successfully applied to the system reliability analysis of continuous structures. The Hutton Field TLP and its one variant, called herein TLP-B, are chosen as TLP models in this paper. The results of several parameteric studies lead to useful conclusions relating to the importance of reducing uncertainties in strength formulae and relating the importance of component post-ultimate behaviour to the systems reliability of such structures.

1. INTRODUCTION

Study on the system reliability analysis has been well appreciated due to its impact on the system-based design for the last two decades and many works have been reported for discrete and continuous structures. This paper addresses the sensitivity characteristics of system reliability to design variables of floating offshore structures aimed at system-based structural design. The necessity to conduct sensitivity studies to examine changes in stochastic parameters, say mean and COV, and distribution types of design variables has been well appreciated [1-3]. The present parameteric study is mainly concerned with the effect on system safety to changes in stochastic parameters of design variables, namely mean and COV, and the effect of post-ultimate behaviour of failed components. For the present purpose the Hutton Field TLP has been chosen as an existing TLP and TLP-B as its variant to compare the safety level of the structures having different types of principle component, i.e. ring-stiffened cylinder (the Hutton TLP) and ring- and stringer-stiffened cylinder (TLP-B). Structural configurations are shown in Fig.1.

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An extended incremental load method [1,2,4] is employed for the system reliability analysis, which is an extension of the conventional incremental load method and can allow for the direct use of strength formulae in the system analysis and also allow for the post-ultimate behaviour of failed components using a simplified model of non-linear behaviour.

2. DESIGN VARIABLES AND COMPONENT STRENGTH

There are many variables affecting the safety level of a structure. For the present study selecting the important design variables, which are supposed to have a comparatively large influence on safety level, has been determined with referring to results of component reliability analysis found in many references [e.g., 2, 3, 5].

As a resistance variable, the strength modelling parameter, X_M must be one of the most important and influential variables with regard to their effect on safety, as can be expected from its important position within the safety margin equation (7). Yield stress, σ_Y is known to be more influential than the elastic modulus, E. The elastic modulus usually has comparatively small influence on safety and so can be treated as a deterministic variable. The influence of geometric properties is also comparatively small because of their small COV. But for a cylindrical member results of component reliability analysis by Das et al. [5] indicated that radius and thickness of cylinder could be influential on safety. As it has been well recognised, the post-ultimate behaviour of failed components is one of the major factors which affect the system reliability and determine the residual strength of a structural system. When any particular component, of which post-ultimate behaviour is not ductile, its failure can greatly affect the re-distribution of load effects of other components and structural stiffness [2].

The range of design variables for the present parameteric study are listed in Table 1 except for the parameter defining the post-ultimate behaviou (see section 5). Throughout the analysis the system reliability index is the average one corresponding to the total average of system failure probability for three wave directions, say 0, 45 and 90 deg.

3. EFFECT OF STRENGTH MODELLING PARAMETER ON SYSTEM RELIABILITY

3.1 Modified Safety Margin Equation

when j components, r_1, ..., r_j, have failed, a general expression of the linear safety margin for the m th failure mode (or failure path) is expressed as Eq.(1) [6]:

$$Z_m = \sum_{k=1}^{j} C_{mk} R_k - \sum_{l=1}^{L} B_{ml} P^{(l)} \qquad (1)$$

where Z_m is the safety margin of m th mode, R_k is resistance of the component k and $P^{(l)}$ is the l th loading acting on the structure. C_{mk} and B_{ml} are resistance coefficient and load coefficient for unit value of the l th load, respectively. j and L are number of failed components and number of loading cases, respectively. When the failure of j th component leads to the collapse of the structure, $C_{mj} = 1.0$. The above saefty margin equation (1) is to be modified in a non-dimensional form as follows to take into account the uncertainty of the strength modelling parameter in the system reliability analysis [2,4]. The strength modelling parameter, X_M is usually defined as:

$$X_M = \frac{\text{actual behaviour}}{\text{predicted behaviour}} \qquad (2)$$

which represents the objective uncertainty of the strength model in reliability analysis [7]. The mean of X_M is referred to as the mean bias μ_{XM} and when there are sufficient data, the randomness of X_M is usually referred to as the modelling uncertainty specified by its COV, V_{XM}. μ_{XM} gives the shifting effect of failure surface by amount of $(X_M - 1)$ as in Fig.2.

Separating the resistance term of component r_j in Eq.(1), which is the last failed component, and considering that its coefficient is unity:

$$Z_m = R_j + \sum_{k=1}^{j-1} C_{mk}R_k - \sum_{l=1}^{L} B_{ml}P^{(l)} = R_j - Q_j \qquad (3)$$

where Q_j is the net load effect on component r_j due to the already failed components, r_1, $r_2, \ldots, r_{j-1}$ and due to the loading acting on a structure, namely:

$$Q_j = \sum_{l=1}^{L} B_{ml} P^{(l)} - \sum_{k=1}^{j-1} C_{mk} R_k \qquad (4)$$

Eq.(3) can be written as eq.(5) by introducing the strength modelling parameter of component r_j, say X_{Mj}:

$$Z_m = X_{Mj} R_j - Q_j \qquad (5)$$

Dividing both sides of the above equation by R_j and re-substituting Eq.(4) for Q_j results in the safety margin in a non-dimensional form which has the same physical meaning as Eq.(1):

$$Z_m = X_{M_j} - \frac{Q_j}{R_j} = X_{M_j} + \sum_{k=1}^{j-1} C_{mk} \frac{R_k}{R_j} + \sum_{l=1}^{L} B_{ml} \frac{P^{(l)}}{R_j} \qquad (6)$$

The term R_k / R_j can be regarded as a function of the resistance variable vectors of components r_k and r_j, i.e. $\{R\}_k$ and $\{R\}_j$, and $P^{(l)}/R_j$ as a function of $\{R\}_j$ and loading variable vector $\{Q\}_j$ acting on the component. Then Eq.(1) can be as:

$$Z_m = X_{M_j} + \sum_{k=1}^{j-1} G_k(\{R\}_k, \{R\}_j) - \sum_{l=1}^{L} G_l(\{Q\}_l, \{R\}_j) \qquad (7)$$

Function G_k represents the contribution of the strength of already failed components r_k ($k = 1, j-1$) on the safety margin and function G_l that of load effects.

Eq.(7) is a feasible way to directly use the strength formulae in the system analysis and allow for the uncertainties in variables without loass of any physical meaning.

3.2 Results

As can be seen in the safety margin equation (7) the strength modelling parameter plays a major role as a resistance variable in the system reliability analysis.

The incremental load method can be easily applied to evaluating the system reliability in the sensitivity study when failure modes are pre-defined. In order to quantify the effects of

μ_{XM} and V_{XM} on the system reliability, the failure modes already identified when μ_{XM} and V_{XM} have the values selected for the standard case (see Table 2) can be used evenwhen they have different values. μ_{XM} and V_{XM} of cylindrical members only are to be varied.

As listed in table 1 five cases of mean bias and seven cases of modelling uncertainty, by varying them within the practical range including the standard case, have been evaluated for the Hutton TLP and TLP-B. Results for the Hutton TLP are presented in Figs.3 and 4 as the relation between β_{sys} and μ_{XM} and the relation between β_{sys} and V_{XM}, respectively. Figs.5 and 6 show the results for TLP-B. As it can be seen in Fig3.3 to 6, β_{sys} is more sensitive to μ_{XM} for both TLP models. When V_{XM} is small, say less than about 10%, there is no change in β_{sys} to μ_{XM}. The effect of μ_{XM} on β_{sys} becomes significant when V_{XM} is greater than about 10%. Even though the effects of μ_{XM} and V_{XM} on β_{sys} may differ depending on several factors from the present results it may be concluded that developmemnt of strength formulae having low modelling uncertainty may be one of the easiest way to raise the system reliability and therefore, to achieve weight saving while retaining the same level of the reliability.

4. EFFECT OF MATERIAL AND GEOMETRIC PROPERTIES ON SYSTEM RELIABILITY

According to component reliability analysis yiels stress, σ_Y, and cylinder radius, R and thickness, t are important variables affecting component reliability. Figs.7 and 8 show the changes of β_{sys} to COV of σ_Y, and R and t for the two TLP models. Both TLP models show similar tendencies of changes in β_{sys}. The effect of variation in σ_Y on β_{sys} for the Hutton TLP is shown to be greater than for TLP-B. From Figs.7 and 8 it seems that R and t are more influential on β_{sys} than σ_Y. But this may be due to that COV of R and t are given as the same value and their effects are probably more reflected in the form of combined action on safety than COV of σ_Y. They are also well outside the practical range of COV variation on R and t.

5. EFFECT OF POST-ULTIMATE BEHAVIOUR ON SYSTEM RELIABILITY

It has been well recognised that the post-ultimate behaviour of any failed component can greatly influence the load redistribution of surviving components and the structural systems stiffness. It therefore affects the residual strength of a structural system and consequently on the structural systems reliability.

5.1 Simplified Model of Non-linear Behaviour

One can calculate the mean load factor at a particular failure stage by using the incremental load method. The load factor is then used to predict the strain state and the structural stiffness. The three-state model [2] shown in Fig.9(a) is employed for the non-linear behaviour in this study. In Fig.9(a) σ' and ε' are the stress and strain normalised by the values corresponding to the ultimate state. $E' = E_T/E$ represents the non-dimensional post-ultimate slope which is related to work softing (or work hardening). η is referred to theresidual strength parameter defined as the ration of residual strength to the ultimate strength of a component. If $E'=0$, then the behaviour becomes the two-state model. In modelling the component load-end shortening curve the followings are assumed:

- In Fig,9(a): when a component is in the intact state the behaviour is elastic (line OA)
  : when one or both ends of an element fail, the behaviour follows the line AB
  : beyond B zero stiffness is assumed with residual strength characterised
  by the parameter η.
- Axial load effect is assumed to be dominant and the same behaviour is assumed for other actions.
- The behaviour of the critical portion of the cross-section is assumed to represent the bahaviour of the whole section.

5.2 Results

In this section TLP-B is chosen to investigate the effect of the post-ultimate behaviour on β_{sys}. Four cases, as shown in Fig.9(b), are considered. Parameters values are listed in Table3.

The results are illustrated in Fig.10 as the relation between β_{sys} and η. For the two-state model, three more cases of η = 0.4, 0.225 and 0.0 are included to more extensively show the effect of η. As expected, β_{sys} is very much sensitive to the post-ultimate behaviour. Even Case 1, which is very close to ductile behaiour (E' = -0.05, η = 0.925) shows a significant reduction in β_{sys}. This may be due to the combined effects of β_{sys} and η. E' reflects the effect of reducing structural stiffness as well as the load effect redistribution amongst the surviving components and η may give the effect of load redistribution. From the figure it can be seen that the three-state model leads to higher β_{sys} than the two-state model, and η is less than about 0.5, the changes of β_{sys} to η is negligibly small. However its effect becomes significant as η approaches unity.

6. CONCLUSIONS

This paper has addressed a sensitivity study for TLP structural system with placing emphasis on investigating the influence of stochastic parameters of strength variables on the systems safety: strength modelling parameter, geometric and material properties. The effect of the post-ultimate behaviour of components has been also investigated.

The sensitivity studies as shown herein must be useful in assessing the parameters perturbation effects on system reliability, and the results, such as the relation of the system reliability index to stochastic parameters of design variables, can provide useful information about the relative importance of design variables in the context of reliability-based design. Finally, in order to provide the designer with a useful criteria or information as an aid to decision making in the design stage, it may be recommended that certain types of sensitivity studies, as illustrated in this paper, must be valuable to intelligently modify the design.

ACKNOWLEDGMENT

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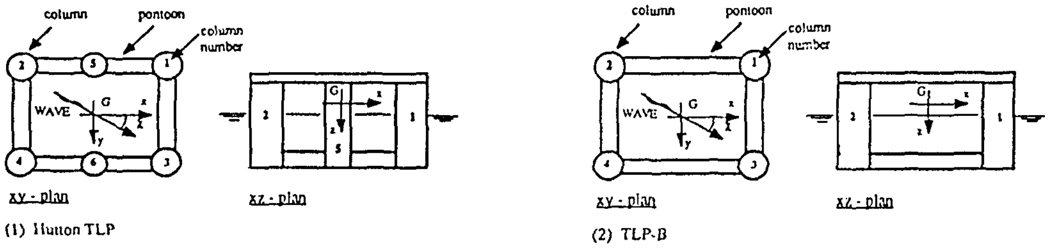


Hutton TLP	*: 6 columns of ring stiffened cylinders*
TLP-B	: 4 corner columns of ring stiffened cylinders in the Hutton TLP are replaced by orthogonally stiffened cylinders and the 2 middle columns are removed.

Fig.1 TLP Models (after reference 1)

Table 1 Range of Variables for the Parameteric Study

(1) strength modelling parameter, XM		
mean bias, μ_{XM}	:	0.90, 0.95, 0.99, 1.05, 1.10
modelling uncertainty, V_{XM}	:	5.0, 7.5, 10.0, 13.0 15.0 17.5 20.0 %
(2) yield stress (σ_Y)		
COV	:	4.0, 8.0, 12.0 %
(3) radius and thickness of cylinder (R and t)		
COV	:	2.0, 4.0, 6.0, 8.0

Table 2 μ_{XM} and V_{XM} of the Standard Case

	ring-stiffened cylinder (Hutton TLP, 6 columns)	ring- and stringer-stiffened cylinder (TLP-B, 4 columns)
μ_{XM}	0.99	0.99
V_{XM}	10.0%	13.0%

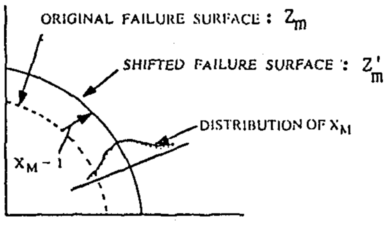


Fig.2 Shift of Failure Surface

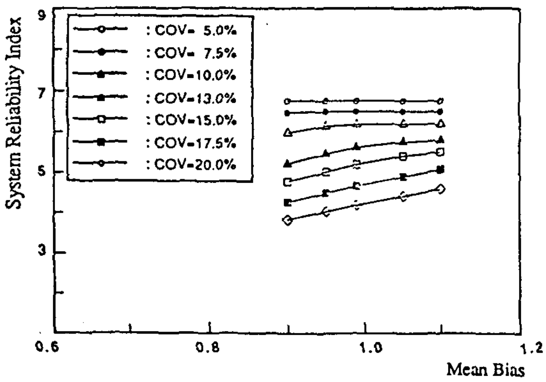


Fig.3 β_{sys} vs μ_{XM} : Hutton TLP

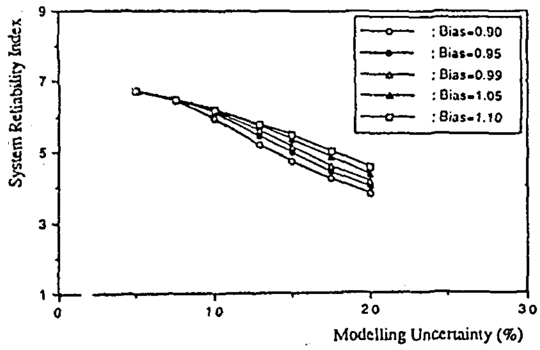


Fig.4 β_{sys} vs V_{XM} : Hutton TLP

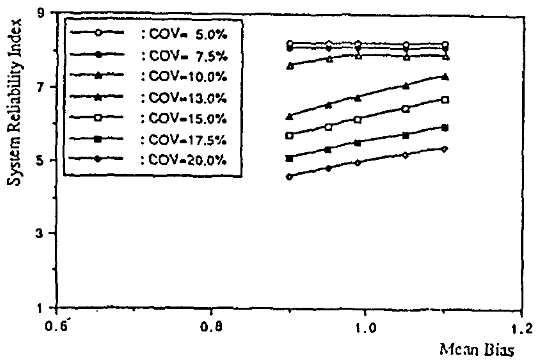


Fig.5 β_{sys} vs μ_{XM} : TLP-B

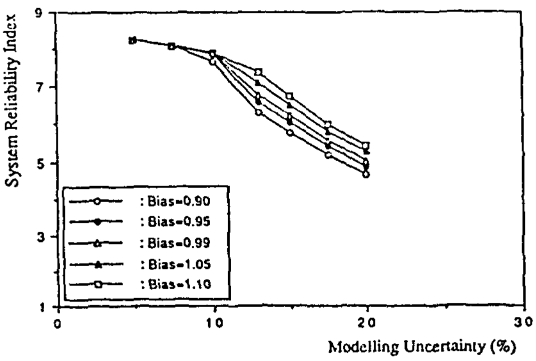


Fig.6 β_{sys} vs V_{XM} : TLP-B

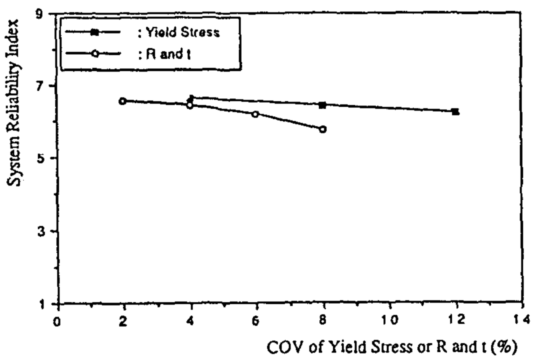


Fig.7 β_{sys} vs COV of σ_Y, and R and t of Cylindrical Components : Hutton TLP

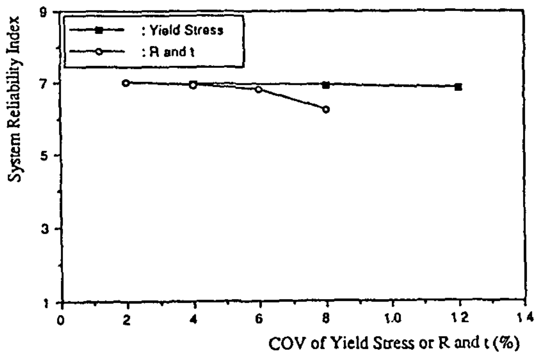
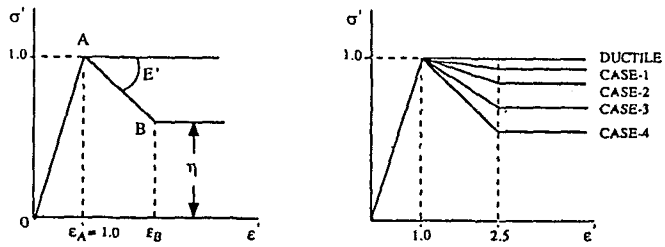


Fig.8 β_{sys} vs COV of σ_Y, and R and t of Cylindrical Components : TLP-B



(a) Non-dimensional Stress-Strain Curve

(b) Non-dimensional Stress-Strain Curves for Case Study

Fig.9 Three-state Model for Non-linear behaviour

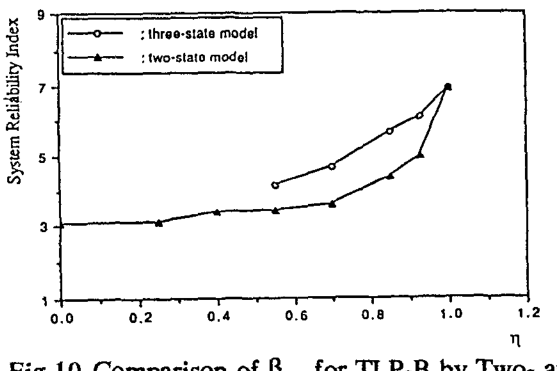


Fig.10 Comparison of β_{sys} for TLP-B by Two- and Three-Stste Model : β_{sys} vs η