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강 구조물의 신뢰성해석에 기초한 구조설계의 개념

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(요 약)

본 논문은 구조적 잉여강도와 신뢰도 사이의 관계를 다루는 것으로서, 적절한 잉여강도와 안전성 사이에 균형을 이루는 강구조물의 구조설계를 꾀하려할 때 손쉽게 사용할 수 있는 간단한 과정을 소개하였다. 이 과정을 여러 경우에 대해 적용한 결과를 잉여강도, 부재의 신뢰성지수 그리고 시스템의 신뢰성 지수들 사이의 관계로서 표현하였다. 이로부터 어느 구조물의 부재가 낮은 신뢰도를 가질 때 구조시스템은 높은 잉여강도를 갖는다는 대체적인 관계가 규명되었다.

본 논문은 구조적 안전성을 구조적 잉여강도와 서로 연관시키려는 시도인데, 그들의 관계를 나타내는 간단한 수식을 제안하였다. 여러 강 구조물의 경우에 대한 기존의 결과를 토대로 구조적 안전성의 허용수준의 범위에 관한 내용을 포함하고 있는데, 이를 기초로하면 초기의 부유식 해양구조물이 과설계 된 것으로 보인다. 실제 구조설계에 적용하기 전에 이 분야에 대해 더 연구해야할 필요성이 있다.

RELIABILITY-BASED STRUCTURAL DESIGN CONCEPT OF STEEL STRUCTURES

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(ABSTRACT)

This paper is concerned with correlating the structural redundancy and the structural reliability, say an attempt to link the structural safety with the structural redundancy. A simple procedure is introduced for easy use in

design of steel structures to achieve a balanced design with adequate structural redundancy and still safety. Several case studies have been carried out by applying the present procedure and the results are illustrated as the relation between structural redundancy, component reliability and system reliability. From this study it has been found that there is already a rough correlation between low component reliability and high reserve strength of structural system.

A relative simple inequality relationship between component and system reliability and structural redundancy has been proposed. Also included is the range of acceptable safety level which have been derived based on the past experiences and as far as the present findings are concerned, the floating offshore platforms as designed seem to have been over-designed. More studies in this field would be required before applying to practical design of real structures.

1. Design Code Format

In reliability-based design we seek to obtain uniform or consistent reliabilities over the range of potential utilisation. In conventional design practice there is a single safety factor in the safety check equation whereas, on the basis of the Level II reliability approach it is possible to derive partial safety factors (PSFs) for use in safety check equations. This provides the basis of the Level I method for use in design which makes little, if any, reference to statistical properties beyond those necessary for defining the more important variables such as nominal yield stress etc. This safety checking format with PSFs can allow for flexibility since they can reflect the overall uncertainties in loading and strength as well as the overall target reliability index.

In its simplest form the safety check equation can be written as:

$$\sum_{i} \gamma_{f_i} Q_{k_i} \leq \frac{R_k}{\gamma_m \gamma_c} \quad (1)$$

which essentially relate nominal or characteristic values of extreme load effects Q_k and ultimate strength, R_k, of the structural component. The γ's are the partial safety factors which reflect the uncertainties in load, γ_{f_i}, in as built strength, γ_m, and also the nature of the structure and the seriousness of the consequences of failure, γ_c, which is linked to socio-economic factors.

API Recommended Practice which dominates the design of offshore platforms in the U.S. uses the Load and Resistance Factor Design (SRFD) format[1]. In this format a safety check equation is of the form:

$$\sum_{k} \gamma_k Q_k \leq \phi_{sys}\ \phi_i\ R_i \qquad (2)$$

where R_i is the nominal strength, Q_k the nominal loading, ϕ_i respective strength factor of the nominal loading and γ_k load factor. System factor, ϕ_{sys} is also added in the partial safety equation to represent the system consequences of a component failure and would be greater than unity. However, in the present LRFD format ϕ_{sys} is taken as unity.

The actual form of safety check equation adopted by the TLP RCC in the model code for structural design of TLPS[2] is somewhat more complex than Eqs. (1) and (2) and checking for component safety is generally done with a three term interaction equation.

$$\sum_{i=1,2,3} \left\{ \frac{\gamma_s Q_{s_i} + \gamma_q Q_{q_i} + \gamma_d B Q_{d_i}}{R_{k_i} / \gamma_m \gamma_i \phi_{sys}} \right\}^{j_i} \leq 1 \qquad (3)$$

where subscripts s, q and d refer to static, quasi-static and dynamic load effect components and B is a systematic modelling or bias factor for the dynamic component. Subscripts i=1, 2, and 3 refer to the equivalent or resolved axial, shear and pressure load and resistance effects, γ_s, γ_q and γ_d are partial safety factors for load effects and are greater than unity. γ_m accounts for uncertainties in the material properties, the γ_i's are modelling uncertainties for the three strength components, and j_i is an interaction exponent for each of these three strength compoonents. ϕ_{sys} is the system factor normally less than unity but which is taken as unity for the present TLP model code. γ_c for socio-economic consequences of failure has been omitted because the more rational approach of selecting the target reliability index from a minimisation of total costs is preferred. This in turn would lead to an adjustment of all the PSFs[3].

2. Significance for Design

2.1 Redundancy Considerations

An efficient structure is one which does not fail, has adequate but not excessive safety and which minimises cost. Inevitably cost is very closely linked to safety factors(reliability index), especially in structures whose scantlings are governed by ultimate strength considerations. Reliability-based design is aimed at achieving designs in which reliability is uniformly distributed. But the present component reliability-based design approach cannot always give uniform distribution of reliability over the entire structure and in some cases the design can be such that failure of any single component causes the structure to catastrophically collapse as a total system. This may be due to lack of redundancy and lack of knowledge about the re-distribution of load effects after failure of any component. These facts have perhaps stimulated the need to introduce system reliability into design.

System performance has been recognised as a part of structural design thinking. A major benefit from incorporating the system capacity into design is the additional structural reserve strength often found due to design symmetry, multiple load conditions, fabrication requirements and design approximations. These additional margins should be examined in assessing the reliability against extreme load and accident conditions.

Specifications in recent years recommend the designer to provide redundancy. Additional members can also raise the degree of structural redundancy. Hence, in the context of system reliability-based design, one should consider structural redundancy characterised as by reserve strength and residual strength.

For ultimate strength collapse a four legged jacket structure which has horizontal chords and single diagonal or K bracings is statically determinate and has very little residual strength when a bracing member is severely damaged or removed. The only source of residual strength is from secondary bending at the ends of the remaining braces or the portal action of the vertical members. X braced systems are much more redundant and have high reserve strengths. Their residual strengths will generally also be high but this will depend on the column slenderness of the compression braces and will be low for slender columns. Multi-leg systems will be stronger still in those planes where three or more legs occur. Then, the choice as to whether the diagonal braces are all oriented in the same direction or are opposed at their connections with the legs has to be made[4] the former generally being preferred if the worst environmental loading is likely to come from one predominant direction. If the braces are then designed to be mostly in tension then their fatigue design at node joints would be more important than if they are mostly in compression. In the latter case low column slenderness and high punching static strength at the node are desirable. Reserve strength ratios, n in most fixed jacket structures are sometimes less than 2.0 but probably average around 2.5. A reserve strength index for well-designed floating offshore structures is recommended to be about 2.0[5].

2.2 Relation between Safety and Redundancy

The system factor (often called system partial safety factor), ϕ_{sys} has close correlation with structural redundancy because the redundancy should play a major role in choosing the value of ϕ_{sys} and can represent the system consequences of a component or member failure.

As Moses[1,6] and Faulkner[3,7]

stated, the system factor should perhaps be incorporated in the safety check equation and should be examined alongside the more logical (in principle) use of a system reliability index, β_{sys}, to derive all the PSFs as the best way of including safety and redundancy considerations in the design process. When using the safety check equation given as Eq. (2), ϕ_{sys} is normally greater than unity while, when using the safety check equation given as Eq. (3), ϕ_{sys} is normally less than unity which is, however, taken as unity in the present codes in use.

Faulkner[3] proposed a simple procedure of calculating the system factor, ϕ_{sys}, with the assumption that the distributions of component strength (or resistance) and lifetime load effect are normal. With this assumption the reliability index is defined in terms of the central safety factor as Eq. (4)

$$\beta = \frac{\theta - 1}{\sqrt{(\theta V_R)^2 + V_Q^2}} \tag{4}$$

where V_R and V_Q are COV of R and Q. $\theta = \underline{R}/\underline{Q}$ and is referred to as the central safety factor. When reliability index, β, is given, the central safety factor is obtained by solving Eq. (4) as [8]:

$$\theta = f(\beta, V_R, V_Q) = \frac{1 \pm \sqrt{1-(1-\beta^2 V_R^2)(1-\beta^2 V_Q^2)}}{(1-\beta^2 V_R^2)} \tag{5}$$

When the sign before the root is negative, Eq. (5) gives a trivial solution. From Eq. (5) the central safety factor for component, θ_{comp} and system, θ_{sys}, is obtained as given β_{comp} and β_{sys}:

$$\begin{aligned} \theta_{comp} &= f(\beta_{comp}, V_{R_{comp}}, V_Q) \quad \text{for component} \\ \theta_{sys} &= f(\beta_{sys}, V_{R_{sys}}, V_Q) \quad \text{for system} \end{aligned} \tag{6}$$

in which β_{comp} and $V_{R_{comp}}$ are component reliability index and COV of component resistance, and β_{sys} and $V_{R_{sys}}$ system reliability index and COV of system resistance. Then, assuming the mean values are characteristic values, it follows that an acceptable multiplicative resistance partial safety factor, ϕ_R, is defined by:

$$\phi_R = \frac{R^*}{\underline{R}} = 1 - \beta\alpha_R V_R \tag{7}$$

where R^* is the "design point" value for maximum probability of failure and α_R is the representative sensitivity parameter given as:

$$\alpha_R = \frac{\theta V_R}{\sqrt{(\theta V_R)^2 + V_Q^2}} \tag{8}$$

If the central safety factor for system, θ_{sys}, is defined as being n times that for a component, i.e., $\theta_{sys} = n\ \theta_{comp}$, the system reliability index, β_{sys}, can be evaluated from Eq. (4) with replacing θ by θ_{sys}. The representative sensitivity parameter,

$\alpha_{R_{sys}}$ and resistance partial safety factor, $\phi_{R_{sys}}$, can be obtained from Eqs. (7) and (8), respectively. An approximation to the system factor, ϕ_{sys} to use with a design based on component failure can be estimated from:

$$\phi_{sys} = \frac{\phi_{R_{sys}}}{\phi_{R_{comp}}} = \frac{1-\beta_{sys}\,\alpha_{R_{sys}}\,V_{R_{sys}}}{1-\beta_{comp}\,\alpha_{R_{comp}}\,V_{R_{comp}}} \qquad (9)$$

For the ranges of n=1.05 to 3.0 and β_{comp} =0.1 to 5.0, when typical values of V_Q=0.2 and $V_{R_{comp}} = V_{R_{sys}}$ =0.15 are assumed, Figs. 1 and 2 show the relation of β_{comp} and n to β_{sys} and ϕ_{sys}, respectively.

The total load factor, λ_T, is defined as the ratio of the system collapse load to the design load, that is the reserve strengtu index[5,8]. Let F_{comp} be the ratio of a component failure load to the design load. The parameter, n, is defined as the ratio of the mean system collapse load to the mean component collapse load. Thus:

$$n = \frac{\lambda_T}{F_{comp}} \qquad (10)$$

and n is referred to as the reserve strength ratio for system(or reserve strength factor).

Consider the case when R and Q are lognormal. Then, ln R and ln Q are normal with means, λ_R and λ_Q, and standard deviations, ζ_R and ζ_R, given by[9]:

$$\lambda_R = \ln \underline{R} - \frac{1}{2}\zeta_R^2, \qquad \lambda_Q = \ln \underline{Q} - \frac{1}{2}\zeta_Q^2$$
$$\zeta_R^2 = \ln(1+V_R^2), \qquad \zeta_Q^2 = \ln(1+V_Q^2) \qquad (11)$$

The safety margin, Z=R-Q, is equivalent to a non-dimensional form:

$$Z' = \frac{R}{Q} - 1 = \theta - 1 \qquad (12)$$

where θ is the central safety factor and also a lognormal variate with parameters:

$$\lambda_\theta = \lambda_R - \lambda_Q = \ln \frac{\theta}{\left[\frac{1+V_R^2}{1+V_Q^2}\right]^{1/2}} \qquad (13.a)$$

$$\zeta_\theta^2 = \zeta_R^2 + \zeta_Q^2 = \ln(1+V_R^2)(1+V_Q^2) \qquad (13.b)$$

Therefore, ln θ is also normal with mean, λ_θ, and standard deviation, ζ_θ Then, the corresponding reliability index to Eq. (12) is given by:

$$\beta = \frac{\lambda_\theta}{\zeta_\theta} \qquad (14)$$

Assume the same value of V_R and V_Q for component and system as the case when R and Q are normal. Then,

$$\zeta_{\theta_{sys}} = \zeta_{\theta_{comp}} \qquad (15.a)$$

If the central safety factor for the system, θ_{sys}, is defined as n times that for a component, θ_{comp}, as before, the parameter λ_θ for system, $\lambda_{\theta_{sys}}$, is expressed from Eq. (13.a) as:

$$\lambda_{\theta_{sys}} = \ln \frac{\bar{\theta}_{sys}}{\left[\frac{1+V_R^2}{1+V_Q^2}\right]^{1/2}} = \ln \frac{n\bar{\theta}_{comp}}{\left[\frac{1+V_R^2}{1+V_Q^2}\right]}$$

$$= \ln n + \lambda_{\theta_{comp}} \quad (15.b)$$

With Eqs. (15) Eq. (14) gives the system reliability index as:

$$\beta_{sys} = \frac{\lambda_{\theta_{sys}}}{\zeta_{\theta_{sys}}} = \frac{\ln n + \lambda_{\theta_{comp}}}{\zeta_{\theta_{sys}}} = \frac{\ln n}{\zeta_\theta} + \beta_{comp} \quad (16)$$

That is, β_{sys} is ($\ln n/\zeta_\theta$) greater than β_{comp}. Eq. (16) is the relation between the reserve strength for system and component and system safety.

In order to evaluate the system factor from Eq. (9), ϕ_{sys}, R_{comp} and R_{sys} are assumed to have means of $\bar{\theta}_{comp}$ and $\bar{\theta}_{sys}$ and COV of V_R, and Q is assumed to have mean of unity and COV of V_Q.

For the same ranges of n and β_{comp} and with the same values of V_R and V_Q as before Figs. 3 and 4 show the relation of n and β_{comp} to β_{sys} and ϕ_{sys}, respectively. Comparing Figs. 3 and 4 with Figs. 1 and 2, it can be seen that lognormal distributions of R and Q give higher β_{sys} and especially, ϕ_{sys} than for normal distributions. Moreover ϕ_{sys} has a very different tendency from that of ϕ_{sys} for normal distributions such that ϕ_{sys} increases as β_{comp} increases with lognormal distributions, whereas it decreases when R and Q are normal. Within practical ranges of n=1.5 to 3.0 and and β_{comp} of 2.0 to 5.0 Table 1 illustrates β_{sys} and ϕ_{sys} when R and Q are assumed normal and lognormal.

The above approximations have merit, because of their simplicity, that the relation of component and system safety to redundancy can easily be predicted for a structure in the initial design stage. However, the system factors should probably be determined from a more rigorous system analysis for the intact and/or a damaged model of the structure. One reflects the reserve strength, while the other the residual strength.

Table 1 β_{sys} and ϕ_{sys} to β_{comp}

(1) when R and Q are normal

β_{comp}	n=1.5		n=2.0		n=2.5		n=3.0	
	β_{sys}	ϕ_{sys}	β_{sys}	ϕ_{sys}	β_{sys}	ϕ_{sys}	β_{sys}	ϕ_{sys}
2.0	3.46	0.71	4.28	0.53	4.78	0.41	5.12	0.34
2.5	3.86	0.69	4.59	0.51	5.03	0.40	5.32	0.32
3.0	4.23	0.67	4.87	0.49	5.25	0.38	5.51	0.31
3.5	4.58	0.66	5.14	0.48	5.46	0.37	5.68	0.30
4.0	4.93	0.64	5.39	0.47	5.66	0.36	5.84	0.29
4.5	5.26	0.64	5.64	0.46	5.86	0.36	6.00	0.29
5.0	5.59	0.63	5.88	0.46	6.04	0.36	6.15	0.29

(2) when R and Q are lognormal

β_{comp}	n=1.5		n=2.0		n=2.5		n=3.0	
	β_{sys}	ϕ_{sys}	β_{sys}	ϕ_{sys}	β_{sys}	ϕ_{sys}	β_{sys}	ϕ_{sys}
2.0	3.64	0.89	4.80	0.84	5.70	0.82	6.43	0.80
2.5	4.14	0.90	5.30	0.86	6.20	0.83	6.93	0.82
3.0	4.64	0.92	5.80	0.88	6.70	0.85	7.43	0.84
3.5	5.14	0.93	6.30	0.89	7.20	0.87	7.93	0.86
4.0	5.64	0.94	6.80	0.91	7.70	0.89	8.43	0.88
4.5	6.14	0.96	7.30	0.93	8.20	0.91	8.93	0.90
5.0	6.64	0.98	7.80	0.95	8.70	0.94	9.43	0.93

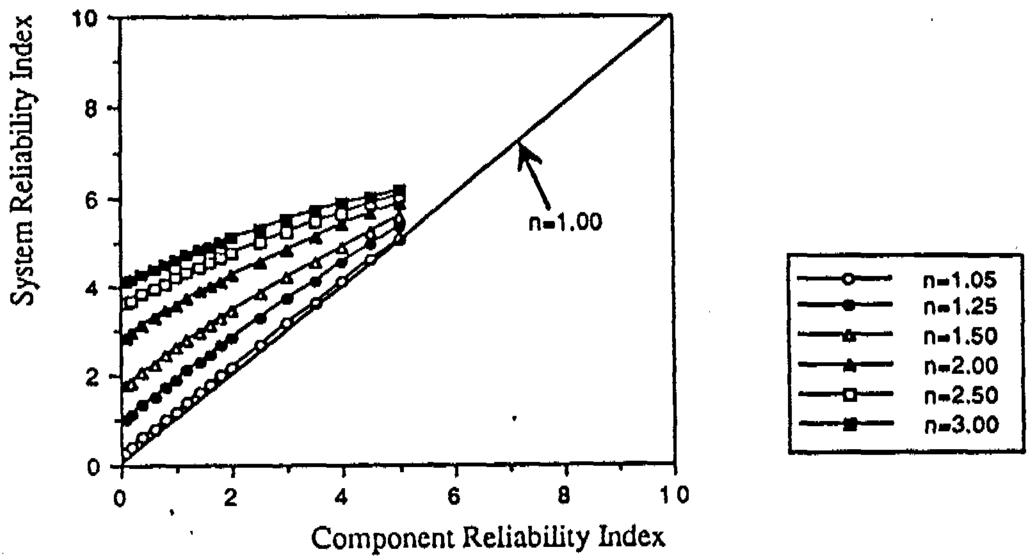

Fig. 1 Relation between n, β_{comp} and β_{sys} (R & Q are normal)

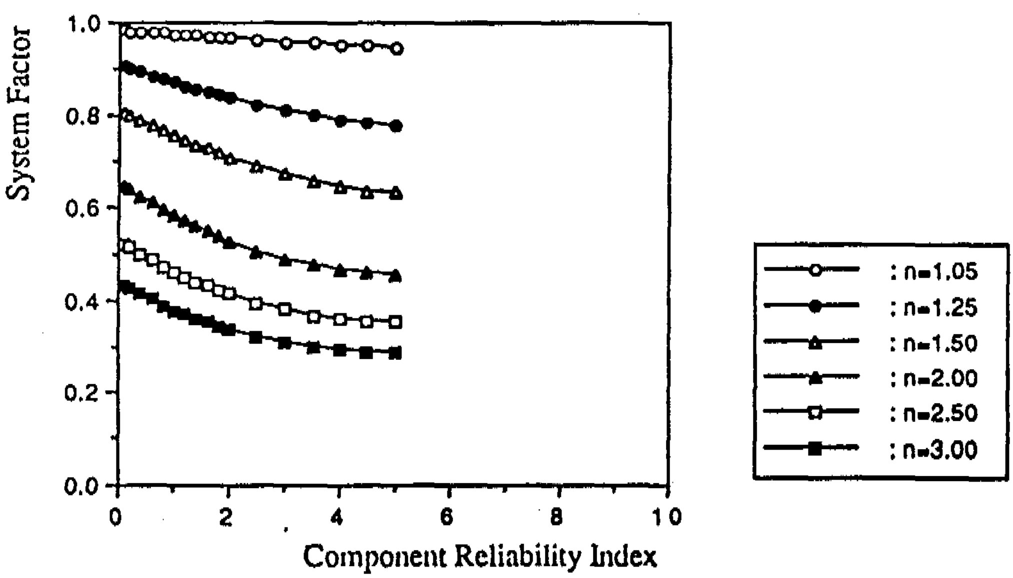

Fig. 2 Relation between, n, β_{comp} and ϕ_{sys} (R & Q are normal)

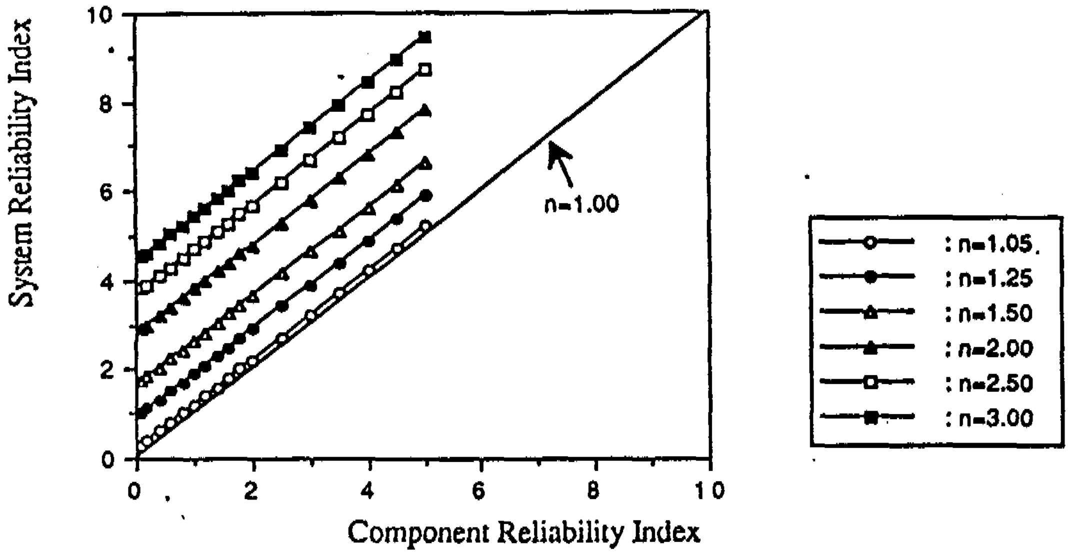

Fig. 3 Relation between n, β_{comp} and β_{sys} (R & Q are lognormal)

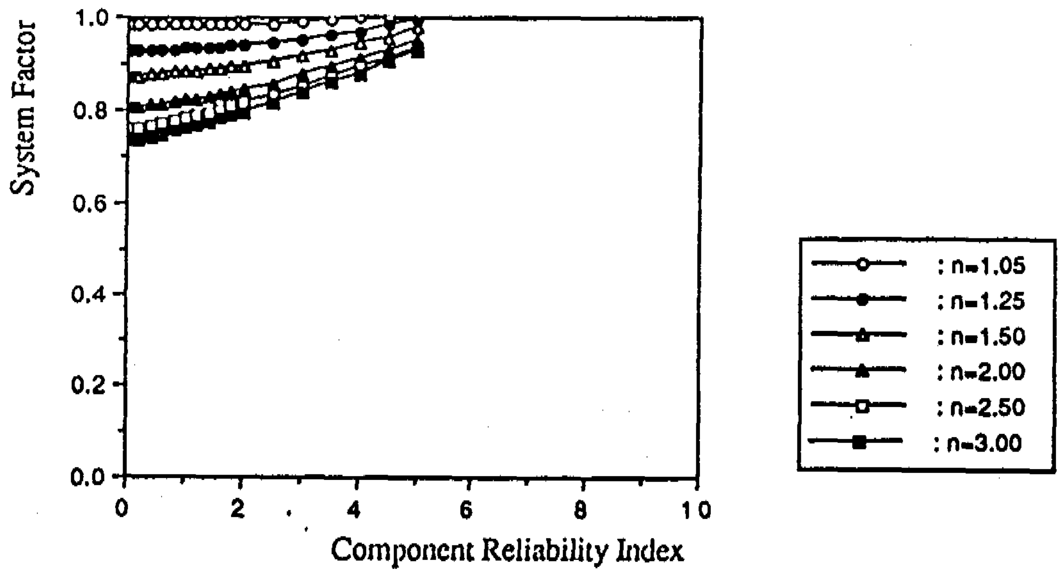

Fig. 4 Relation between n, β_{comp} and ϕ_{sys} (R & Q are lognormal)

2.3 Acceptable Safety Levels

In design we should recognise that rational safety levels must pay some regard to the definition of safety as applied in judicial proceedings. This pertains to collapse of the overall structural system when the economic and human consequences become significant. Nevertheless by tradition and for convenience, specifications have to be prepared which deal with components, beams, columns, connections and so on. Recognising also that formal prescribed notional safety has very little if any correlation with actuarial safety for most structures the way would seem open to:

(a) Progressively lower component notional safety levels, especially as our knowledge of loading and response steadily improves.
(b) Introduce system safety in design on a consistent basis which recognises the hierarchical type of structure and components being considered, the degree of residual strength and reserve strength present, and a start should now be made to formalise in design codes.
(c) Develop a rational relation between component and system safety. A non-redundant structure would need a higher safety margin than a redundant one to achieve the same acceptable level of damage tolerance.

Of course it will always be important to ensure that with the lowering of component safety the probability of fatigue or overload damage in service is kept to an acceptable level mainly to reduce the need for repair costs. Nevertheless, from (a) there could be significant scope for cost and weight savings.

If one examines present practice, Table 2 attempts to give the present relation between average component safety indices and reserve strength ratio, n, beyond first component failure for a variety of steel structures[10]. Some of the values are judgements to aid discussion.

It would seem that with the exception of Naval ships there is already a rough correlation between low β_{comp} and high n (and even higher reserve strength index λ_T) and it would seem there is merit in pursuing such studies. They might lead ultimately, for example, to relations for use in designs as[10]:

$$\beta_{comp} + n \leq 5.0 \qquad (17)$$

In the discussion of reference [10] a lower value of 4.5 was suggested by Frieze for the right hand side, and certainly the inequality was suggested as an upper limit. From Eq. (6) or (16) we can obtain the reserve strength ratio, n, given that β_{comp} and β_{sys}. That is:

(1) when R and Q are normal, from Eq. (6)

$$n = \frac{f(\beta_{comp}, V_{R_{comp}}, V_Q)}{f(\beta_{sys}, V_{R_{sys}}, V_Q)} \quad (18)$$

function f is evalusted from Eq. (5)

(2) when R and Q are lognormal, from Eq. (16)

$$n = \mathrm{Exp}[\zeta_\theta(\beta_{sys} - \beta_{comp})] \quad (19)$$

When β_{sys} is 4.0 to 6.0, n values by Eq (18) and (19) are plotted against β_{comp} as shown in Fig. 5, in which the points corresponding to various structures of Table 2 and Eq. (17) are also included. Comparison of Eq. (19) to (18) shows that lognormal distributions of R and Q may give more realistic predictions for comparison with n than normal distrbutions especially for the higher β_{sys}values. By reference to Eq. (17) in Fig. 5 semi-submersibles and the North Sea TLP seem to be overdesigned. For floating offshore structures, if the allowable β_{sys}(β°_{sys}) is provisionally chosen to be not greater than 6.0, well-designed structures possibly lie within the region determined by the inequality equation, (17) and the following equation derived from Eq. (19):

$$\beta_{comp} + \frac{\ln n}{\zeta_\theta} \le \beta^{\circ}sys\ (=\text{say } 6.0)$$

The thick solid line in Fig. 5 represents the boundary determined by Eqs. (17) and (20).

Table 2 Component Safety and Subsequent System Redundancy(average values only)

Structure	Component category β		System category n	
Fixed Platforms	2.3	low	1.7	high
Buildings	3.0-3.5	average	1.5	average
Bridges	3.7	average	<1.2	low
	4.8	high	<1.2	low
Merchant Ships	3.5-4.0	average	<1.2	low
Semi-Submersibles	>4.0	high	>1.5	average
North Sea TLP	>4.5	high	1.5	average
Naval Ships	2.2	low	<1.2	low

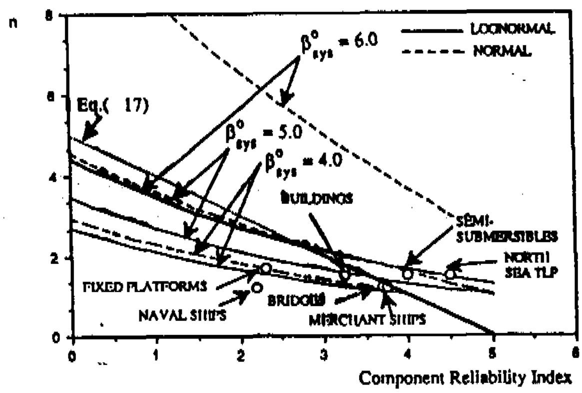

Fig. 5 β_{comp} and n

The use of n, the system strength to component strength ratio, is preferred rather than the more popular reserve strength index, λ_T, [10]. This is because λ_T inevitably contains the safety factor of the most critical component within it and therefore would cloud the "high-low" relationship which Table 2 seems to establish. The choice of β_{sys} would then follows naturally from such studies. Alternatively, a system factor, ϕ_{sys}, could be applied in component design as recommended by Moses[1] and by Faulkner[3,7].

The inequality sign in Eqs. (17) and (19) recognises that some acceptable safety levels may very well be lower than these limits, and also the passage of time would naturally require safety levels to reduce in a rational code. Moreover, it recognises that perhaps the most rational safety level should really be chosen on economic grounds unless massive human life were really at risk-as they are in aircraft.

3. Discussion

The simple procedures introduced in Section 2 may be helpful to roughly predict the system safety level and structural reserve and residual strengths, and also to choose an acceptable safety level in the design stage. Levels of safety vary quite widely depending on structural type and behaviour of component in a structure, especially on the post-ultimate behaviour of a failed component. It has been suggested that they may sensibly be linked to the reserve strength ratio for the system, n, and component strength, as given by Eqs. (17) and (20). It should be pointed out that first generation semi-submersibles and TLP structures would appear to be significantly overdesigned in the light of the present studies [see Fig. 5]. Therefore, acceptable safety levels may be lowered than those used in present design, and this would also appear to be justified in the light of service experience.

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