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API RP2A practice for the 1990s – a step forward

P A Frieze, BSc, PhD, CEng, FRINA, MIStructE
Advanced Mechanics & Engineering Ltd

SYNOPSIS

In this paper the background to the new limit state version of API RP2A (known as API RP2A-LRFD) and its safety format are briefly reviewed. Differences between the formulations used in recent issues of RP2A and LRFD are described. The calibration procedure used in the derivation of partial load and resistance factors is discussed and consequences for new designs in the Gulf of Mexico, West Coast USA and North Sea are summarised. The paper closes by briefly reviewing the advantages of adopting an LRFD format for design.

INTRODUCTION

The American Petroleum Institute (API) have just published a draft limit state alternative to the 18th edition of API RP2A 'Recommended practice for planning, designing, and constructing fixed offshore platforms'.[1] This alternative, known as load and resistance factor design (LRFD) in the United States, will offer a limit state framework for designs to be executed using procedures identical in many cases to those already contained within RP2A.[2] The major difference arises in the use of partial load and resistance factors to be applied as multiplying factors to each of the three main types of loads – dead, live and environmental – and to each component strength (resistance) equation. Component is here used in the general sense in that it includes members, joints, piles etc, under separate as well as combined load actions.

The API committee set up to execute this development, TAC-22, started work in 1979 with the objective of basically developing a limit state equivalent to RP2A. Initially, therefore, the aim was to derive load and resistance factors which would produce designs very similar to those of RP2A. This would lead to components with very different safety levels when assessed in reliability terms. With time the strategy slowly changed, the objective becoming more one of achieving uniform safety levels but still on average realising similar safety levels to those of RP2A. This process is known as calibration.

This objective has only been realised in part. This is understandable. Judicial remedies use 'engineering experience' as a basis for decisions. In some cases achieving uniform reliability would have required not insubstantial differences to RP2A design requirements. Such step changes render engineering experience doubtful and should only be introduced gradually. The TAC-22 committee appears to have been conscious of this in developing RP2A-LRFD.

As a consequence of aiming at more uniform reliability levels, however, some penalties have been introduced compared with RP2A for components subjected to extreme environmental conditions, while some gravity load dominated designs are possibly heavier than they would be if completely uniform reliability had been realised. The TAC-22 committee sought to maintain this differential for gravity load dominated designs because of a concern for the very frequent use of non-redundant deck leg configurations.

Dr P A Frieze graduated from the University of Western Australia in Civil Engineering. He obtained a PhD in Structural Engineering from Imperial College, University of London. He lectured at Glasgow University before moving to Wimpey Offshore and then John Brown. He was appointed to University College London, firstly as Manager of the London Centre for Marine Technology and, secondly, as Manager of the Underwater NDE Centre. He joined AME as Project Manager of an EEC funded project concerned with Platform Lifetime Assessment through Analysis, Inspection and Maintenance.

The full scope of the TAC-22 work was substantial.[3] It was presumably not made easy by the continual updating of RP2A which frequently was a result of advances arising from the TAC-22 work anyway. It should be recalled that the LRFD work began in 1979 when the 10th edition was the current version. Now the draft LRFD is an alternative to the 18th edition of RP2A. Reliability analysis was used whenever sufficient information was available. Thus, all jacket members, joints, piles and loads, including dynamic load effects, were handled using this approach. In the case of earthquake loading, pile sleeves and topsides design, which was to be based on the 1986 AISC-LRFD component formulations, where insufficient data were available, a direct or brute force approach to derive the partial factors was adopted.

Twelve typical Gulf of Mexico platforms were initially surveyed to obtain representative ranges of gravity to environmental load ratios, axial load to bending moment ratios in members and joints, and interaction ratios for all important components as well as those experiencing high utilisation. The corresponding load cases were also identified.

Following calibration, six platforms were considered in detail to ascertain the impact of using LRFD.[4] Three were selected where a static wave approach was appropriate, and thereby provided a basis for refining the load and resistance factors. These were in less than a water depth of 100m. The fourth was in some 285m of water and was used to check the inertial load factor, covering dynamic effects. The last two were used in the calibration of the uncertainties associated with earthquake design and to derive seismic load and resistance factors. These jackets stood in 70 and 225m of water.

This paper reviews the LRFD safety format and the adopted calibration procedure. The impact on new designs is considered, firstly for Gulf of Mexico/West Coast conditions, and then for North Sea conditions. The advantages of moving to an LRFD (or limit state) format in place of the existing working stress approach are indicated, and the paper concludes by assessing the role of LRFD for jacket designs in the 1990s.

RP2A-LRFD SAFETY FORMAT

The basic safety format adopted in LRFD is:

$$\phi R_n = \gamma_{D1} D_1 + \gamma_{D2} D_2 + \gamma_{L1} L_1 + \gamma_{L2} L_2 + \gamma_W \left(W + \gamma_{dyn} D_n \right) + \gamma_E E \quad (1)$$

where ϕ is the resistance factor (< 1.0);

R_n is the component nominal design resistance (acknowledged to generally be the mean value,[3]);

γ are the global load factors (> 1.0 unless loads are opposing);

D, L W, E and D_n are load effects due to dead, live, static environmental and seismic loading, and the inertial component of dynamic response.

Values of ϕ vary and are dependent on component type and loading. Some typical values are listed in Table I.

Load factors are given for two primary load combinations of operational and extreme. For the latter, the case where gravity and environmental load effects oppose each other is also covered. Factors were specifically derived for seismic conditions while recommended values to account for the uncertainties associated with the various stages of loadout, launch, etc, were also given. The load factors are listed in Table II.

Equation 1 indicates that dead and live loads are separated into two categories. Briefly D_1 relates to self-weight, permanently fixed equipment, hydrostatic forces including buoyancy, and enclosed water. D_2 covers moveable equipment (drilling and production) and equipment and facilities that can be added or removed from the platform such as living quarters, helideck and other life-support equipment. Loads L_1 relate to consumable supplies while L_2 covers operational forces (drill string manoeuvres, crane and machine operations, vessel mooring, helicopter loadings) including their dynamic effects.

Table II indicates that, when present, loads in either dead or live load category attract the same factor. It is anticipated with time that different factors may be introduced to account for the differences in uncertainty associated with each subcategory.

DIFFERENCES BETWEEN LRFD AND RP2A

In developing LRFD, the intent was not to depart significantly from RP2A. However, in the process it became clear that some features of RP2A needed to be improved. With time, many of these improvements were taken up by RP2A so the calibration process itself involved a 'moving target'. This is one of the strengths of the API framework for recommended practices (RP) in that updates are regularly introduced, but usually only after careful review and consideration by those involved in the design and operation of the units to which they refer.

Table I: Resistance factors

Component		ϕ
Tubular members		
Tension yield		0.95
Axial compression (column and local buckling)		0.85
Bending		0.95
Shear (beam and torsional)		0.95
Hoop buckling		0.80
Tubular joints		
K	All loads	0.95
T, Y, X	Axial tension	0.90
T, Y, X	Axial compression, in-plane and out-of-plane bending	0.95
Piles		
Soil strength:	compression and tension	0.80
	seismic	0.70–0.80
Grouted pile-sleeves		
Axial load		0.90
Deck and other components (designed to AISC-LRFD)		
Compression, bending, tension yield on gross section		0.85*
Shear		0.90*
Tension fracture on net section		0.70*
Tension, pin connected members		0.40
Shear, pin connected members		0.55
Bearing, pin connected members		1.25

* Increase by 0.1 in the presence of seismic loading.

LRFD was issued as an alternative to the RP2A 18th edition. To identify the differences, however, use was made of the 17th edition as the 18th was not available at the time. Table III lists the substantive changes between RP2A and LRFD.

The table shows that the major changes have concentrated on local tubular strength and a more explicit definition of loads and their combinations. Consistent with a limit state approach to design, conservatisms inherent in ignoring plastic capacities in (particularly stocky) tubulars have been reduced, and the inappropriateness for tubulars of AISC-wide flange formulations recognised. Punching shear as a method for designing tubular joints has finally been phased out after many years of being the only approach available, although latterly it has been an alternative to empirical formulations determined from reasonable scale test results.

With limit state methodologies careful consideration has to be given to load categorisation. Anticipating possible future needs, both dead and live loads have been divided into two categories, the bases for which are summarised in Table III. Opposing loads need specific attention, especially when they are of a similar magnitude, as relatively small changes arising from inherent variabilities can lead to dramatic changes in nominal design forces, and in the associated level of safety. Including extreme inertial load in Table III is not meant to imply that dynamic enhancement has not been previously considered. It is mentioned with the intent of drawing attention to the need to now separate the 'static' and 'dynamic' components of environmental loading as they attract different load factors.

Table II: Load factors

Loading	γ_{D1}	γ_{D2}	γ_{L1}	γ_{L2}	γ_{W}	γ_{dyn}	γ_{E}
Operational conditions	1.3	1.3	1.5	1.5	1.2	1.25	–
Extreme conditions	1.1	1.1	1.1	–	1.35	1.25	–
For opposing gravity and environmental actions	0.9	0.9	0.8	–	1.35	1.25	–
Seismic conditions	1.1	1.1	1.1	–	–	–	0.9
Loadout, launch and lift	1.3	1.3	1.3	–	1.3	1.3* 1.15+	–
Tow, on-bottom w/o piles	1.1	1.1	1.1	–	1.35	–	–
Additional local effects during lifting:							
padeyes, etc and adjoining structure	1.33	1.33	1.33	–	–	–	–
other involved members	1.15	1.15	1.15	–	–	–	–

* offshore
\+ onshore or sheltered waters

Table III: Change in criteria between RP2A (17th ed) and LRFD

Criterion	*Justification*
Tubular bending	To take advantage of plastic hinge capacity.
Hydrostatic pressure hoop buckling	RP2A too conservative with lower buckling coefficient and SF = 2.0. Hydrostatic pressure is almost deterministic (COV = 0.05 taken in calibration).
Interaction – axial and bending (w/o column effects)	RP2A linear relationship relevant to wide-flange sections. Cosine form in LFRD more appropriate to tubulars.
Tubular joints	Punching shear omitted from LRFD.
Gravity load categories	Both dead and live divided into two categories; dead loads according to whether items are fixed or not, and live loads according to duration.
Opposing loads	Specific clause in LRFD to cover gravity loads opposing uplift due to overturning under extreme wave conditions.
Extreme inertial load	To enable the uncertainties associated with dynamic response to be treated independently from those associated with 'static' response to environmental loading.

CALIBRATION PROCEDURE

As indicated in the introduction, 'calibration' was used to derive the load and resistance factors. This aims to realise similar levels of safety (reliability) for components designed in accordance with the new code – here LRFD, as for those designed in accordance with the existing code – here RP2A. A desirable feature of calibration will also involve realising more uniform levels of reliability in the new code.

Reliability analysis procedures were used to establish safety levels. A large range of these exist, many significantly in advance of those used in calibration or that might be used in routine assessments. The most useful for calibration, or for the derivation of load and resistance factors to achieve a particular level of reliability (1×10^{-4} per annum is a popular choice in this connection), are the so-called level 2 procedures. These make use of the first and second moments (mean and variance) of the known probability distributions describing each of the variables in a failure (design) equation. For ease of understanding, the mean and variance are more usefully considered as bias and coefficient of variation (COV).

An approximate but very useful level 2 procedure is the so-called mean-value first-order second-moment (MFOSM) method, for which exact solutions to the reliability index (β) equation exist if the resistance and loading can be treated as variables having normal or log-normal distributions.

The normal form is given by:

$$\beta = \frac{\bar{R} - \bar{Q}}{\left(\sigma_R^2 + \sigma_Q^2\right)^{0.5}} \qquad (2)$$

where Q refers to (generalised) loading, σ is standard deviation, and a bar indicates mean value.

The log-normal description is:

$$\beta = \frac{\ln\left(R_{50}/Q_{50}\right)}{\left(\sigma_{\ln R}^2 + \sigma_{\ln Q}^2\right)^{0.5}} \qquad (3)$$

where 50 indicates the 50th percentile or median.

If coefficients of variation (V) are less than 30%, equation 3 can be approximated by:

$$\beta = \frac{\ln\left(\bar{R}/\bar{Q}\right)}{\left(V_R^2 + V_Q^2\right)^{0.5}} \qquad (4)$$

Introducing θ as the global safety factor, which is given by $\bar{R} \div \bar{Q}$ equations 2 and 4 can be rewritten after some rearrangement as:

$$\beta = \frac{\theta - 1}{\left(\theta^2 V_R^2 + V_Q^2\right)^{0.5}} \qquad (5)$$

and:

$$\beta = \frac{\ln\theta}{\left(V_R^2 + V_Q^2\right)^{0.5}} \qquad (6)$$

The global safety factor is related to the nominal design resistances R_n and loadings Q_n and a working stress code safety factor SF as follows:

$$SF = \frac{R_n}{Q_n} \quad R_b = \frac{\bar{R}}{R_n} \quad Q_b = \frac{\bar{Q}}{Q_n} \qquad (7a)$$

Table IV: Variable biases and COVs

Variable		*Bias*	*COV*	*Comment*
Loads:	Dead	1.0	0.08	Originally based on building loads but improved weight control expected offshore. Assumed COV = 0.05 for weight variation and 0.05 for analysis ~0.08. Weight growth ignored.
	Live	1.0	0.14	No firm evidence for under- or over-prediction. Assumed inherent variability COV = 0.1 plus 0.1 for analysis ~0.14. Weight growth ignored.
	Environmental (wave)	0.7	0.37	Derived from specific 8 leg jacket study.[5] Supplemented by simple model – see text. Assumes 20 year life and 100 year design wave.
	Dynamic amplification	1.0	0.60	Derived for hybrid time-frequency domain analysis. COV function of period, damping, ocean spectra, transfer function definition, member force transfer and DA analysis PRAC (83–22). Period dominant parameter. COV thus platform dependent[6]
Yield stress		1.1	0.08	Bias and COV based on low-strain rate, possibly static, test values.
Tension yield		1.1	0.13	As for yield but includes dimensional variability COV of 0.05 plus additional material variability for plate subjected to strain hardening.
Tubulars:	Compression	1.12	0.15	Includes test material and geometry biases an variabilities. Calculated from Table 3.14 of PRA 85–22 and Table 2.3 of PRAC 87–22 after introducing a yield stress bias of 1.05 for λ = 1.2 and 1.4 in accordance with Table 3.11 of PRAC 85–22.
	Bending	1.26	0.11	Design equation approximates lower bound to test data. Modelling error bias ~1.26 for fully plasticn sections, and 1.38 for non-compact sections. COV comprised 0.06 for test scatter, 0.05 for dimensional variability and 0.08 for material uncertainty.
	Hydrostatic	1.10	0.13	Bias entirely due to material bias since design equation now approximates mean of test data. COV possibly related to test variability only. For safety index evaluation, COV for hydrostatic load taken as 0.05.
Joints:	T,Y DT – compression	1.17	0.11	Bias and COV based on mean curves to test data augmented by 1.1 and 0.08 to account for material bias and variability.
	– tension	1.55	0.43	
	K – axial	1.28	0.19	
	– IPB*	1.35	0.16	
	– OPB+	1.29	0.17	
Piles		1.00	0.20	Considerable judgement used in adopting these values. Other assessments have found: for clay 0.79, 0.2–0.4 and 1.09, 0.26; for sand 1.07, 0.46 and 1.40, 0.45.
Pile-sleeves		–	–	Brute force approach used.

* IPB = in-plane bending
\+ OPB = out-of-plane bending

$$\theta = \frac{R}{Q} = \frac{R_b}{Q_b}\,\frac{R_n}{Q_n} = \frac{R_b}{Q_b}\,SF \qquad (7b)$$

where subscript b indicates bias, ie the ratio of actual to nominal. So, for example, when a nominal design strength approximates the mean strength as found from experimental results, R_b = 1.0. For RP2A, SF = 1.67 (= 1/0.6) under operational conditions and 1.25 (= 1.67/1.33) under extreme conditions.

The equivalent simplified LRFD equation is:

$$\theta = \frac{R_b/\phi}{(D_b/\gamma_D + L_b/\gamma_L + W_b/\gamma_W)} \qquad (8)$$

For the determination of safety indices, the biases and COVs listed in Table IV were adopted. These values represent the combined uncertainties in each case and take account of testing uncertainties, differences between test results and strengths as predicted using the design equation (usually called modelling uncertainty parameter), material variability (yield stress bias and COV of 1.10 and 0.08 'added' in all relevant cases), dimensional variations, and, in the case of columns, tolerances. In the case of environmental modelling a simplified model was introduced which related wave force F, design wave height H raised to a power α, and an analysis factor A, as follows:

$$F = AH^{\alpha} \qquad (9)$$

For a simple structure, a = 1.0 for inertia dominated wave forces, 2.0 for drag dominated forces, > 2.0 for drag dominated conditions involving deck inundation, and ~ 3.0 in the case of some deck leg components. The ocean test structure was used to establish the probabilistic description for A: bias = 0.93, COV = 25%, distribution log-normal.[7] An exact analysis was used to establish lifetime wave force bias and uncertainty from

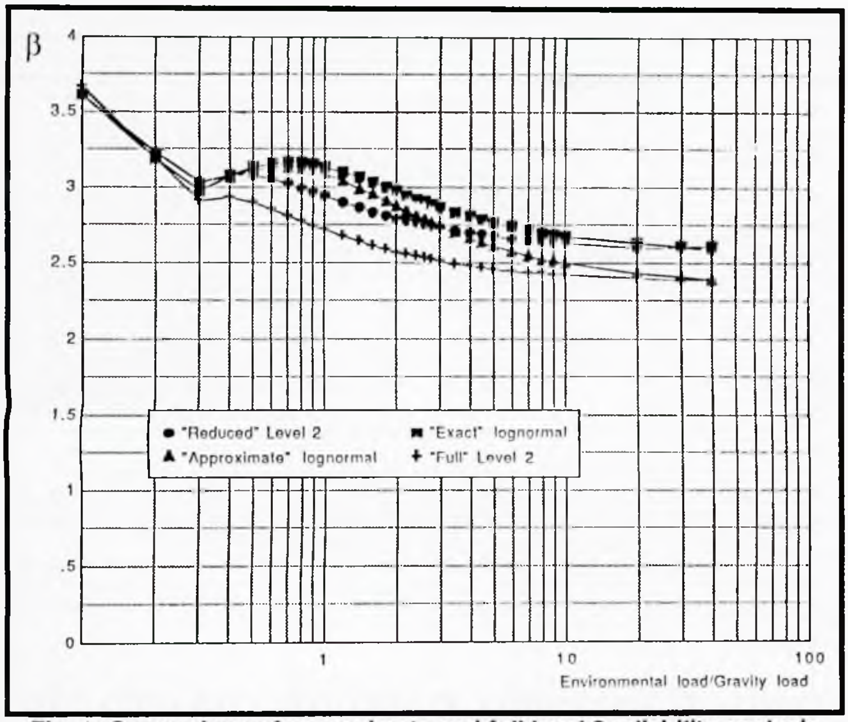

Fig 1: Comparison of approximate and full level 2 reliability analysis solutions for column under environmental and gravity load ratios

Table V: Average reliability indices

Component		*RP2A*	*LRFD*
Yield tension		2.05	2.31
Bending		2.91	2.78
Column2.33		2.70	
Hydrostatic*		4.15	3.01
Foundation		2.18	2.25
Joints:	T, Y, DT Compression	1.81	2.49
	T, Y, DT Tension	1.22	2.01
	K axial	2.18	2.42
	K IPB	3.60	2.75
	K OPB	3.12	2.54
Piles sleeves+:			
	w/o shear keys	4.13	4.14
	w shear keys	3.77	3.78

Notes: 1. Averages apply for environmental/gravity load ratios = 2 to 40 except foundations where 0.6 to 2. Live load = 3 x dead load.
2. Strength formulae relevant to RP2A 12th Edition and PRAC 81–22.

* Calculated from Table 2.9 of PRAC 87–22.
\+ Calculated from Table 4.2 of PRAC 87–22.

which values for α of 2.2 and V_H of 0.25 were derived for more general use. When fed back into equation 9, the environmental load bias and COV shown in Table IV are obtained.

For this MFOSM method, the total bias is simply the product of all the biases while the total COV is found from the following equation, using v to signify an individual COV,

$$\left(\sum v^2\right)^{0.5} \qquad (10)$$

The MFOSM method was initially used in the calibration process. Subsequently, from PRAC 81-22 onwards, an advanced form of level 2 analysis was adopted. Referred to as AFOSM, this technique frequently begins with the mean value solution, equations 2 or 3, and then iterates to the so-called failure point. This point approximates the maximum failure probability value on the n-dimensional failure surface of the system under consideration, when this is expressed in terms of the basic variables, eg thickness, yield stress, length, etc. However, in adopting this approach, the total uncertainty for resistance was still evaluated using equation 10 and was thus not expressed in basic variable terms. This reduced form of AFOSM introduces errors into the determination of β as indicated in Fig 1. Here, β are compared for columns when evaluated for a range of environmental to gravity load ratios (D:L = 1:3) using equations 3, 4 AFOSM (reduced), and AFOSM (full).

The exact log-normal (equation 2) and AFOSM (reduced) evaluations are seen, in Fig 1, to coincide where one load dominates; this is to be expected. The approximate log-normal solution (equation 4) departs from these as environmental load dominates because of the inaccuracies associated with using a COV > 30%. The AFOSM (full) results are rotated with respect to those of the AFOSM (reduced) approach so that they generally lie below those found by the less accurate alternative. The maximum difference in β between the reduced and full solutions is about 0.2. It is unlikely this difference will have a major impact on any load and resistance factor derivations because of the robustness of the calibration procedure to changes of this type. This has been clearly demonstrated in a number of the PRAC reports.

Reference 6 summarises the average reliability indices obtained for RP2A, and for LRFD using the relevant load and resistance factors for some of the jacket components. These are tabulated here in Table V together with average indices for the remaining components extracted from the relevant PRAC reports. The notes accompanying Table V (and taken from Ref 6) indicate that these averages do not necessarily reflect LRFD as it is currently formulated. However, it is understood that use of the exact LRFD formulations would make little difference to the results.

It is important to appreciate that these averages apply to ratios of environmental to gravity loads of between 2–40 in relation to members and joints and between 0.6–2 for foundations. These were identified as the relevant ranges from the platform surveys executed in the early part of the work. The results of the survey indicated that the most highly utilised members were diagonal braces for which axial load was the dominant action. Horizontal braces had a more uniform spread of the axial load component but they were not as heavily utilised as the diagonal braces. Deck and jacket legs were sometimes relatively well utilised, as were piles, but these showed a greater variation from platform to platform. Of the joints, T were occasionally heavily utilised followed by X and TY. The survey also made it clear that for all jackets' members, including deck legs, the extreme case governed. Only in the case of deck braces was the operating condition the more onerous.

Because of the dominance of the extreme condition in determining jacket utilisation ratios, calibration proceeded on the basis of the safety index comparisons in the above range of environmental to gravity load ratios, ie 2–40 for members and joints and 0.6–2 for piles. However, in conducting comparisons on individual strength criteria, eg columns, T-joints, etc this was executed over a range of 0.1–40 thus also involving dominant gravity load conditions. It appears that it was from an examination of the variation of reliability indices in the environmental to gravity loading range 0.2–6, particularly for tension yield, piles and K-joints that led to the introduction of dead and live load factors under extreme conditions of 1.1. Previously, a load factor of 1.0 had been proposed (see Fig 4 of Ref 6 but note the legend is interchanged).

CONSEQUENCES FOR NEW DESIGNS

Gulf of Mexico/West Coast

Because the calculation of reliability indices takes full account of real strengths and loadings and of code safety factors, changes in average indices will indicate whether heavier or lighter structural components will result from the introduction of new strength formulations, loading requirements or safety formats. On the basis of Table V, the effect of introducing LRFD can be summarised as:

1. Tension members, columns, T, Y, DT joints – heavier;
2. Bending, hydrostatic (and combined load cases), K(IPB, OPB) – lighter.

Further estimates as to the extent of the consequences can be found from simple comparisons, assuming full utilisation as shown in Table VI, where safety factors have been calculated for the cases of short and medium length columns and tension members. This simple comparison suggests that braces dominated by axial load under extreme conditions could be some 10–15% heavier than at present and the jacket legs might also be penalised. However, this assumes full utilisation, and as indicated in the PRAC surveys and summarised in Ref 4, few members are so subjected.

From the PRAC studies, the number of components in platforms A–D for which utilisation exceeded unity under either RP2A or LRFD assessments, is summarised in Table VII. The number is greater for LRFD but compared with the total number of checks few members would require resizing if LRFD were to be adopted. More specifically, Ref 6 reports on a resizing exercise specific to the 'seismic' platforms E and F, in which weight changes of + 0.7% and – 0.5% were obtained for the jacket structures. To avoid penalties to the piles, a ϕ factor of 0.7 was found to be necessary (see Table I).

On average, the PRAC investigations found that overall weight requirements would alter little with the introduction of LRFD. However, on an individual component basis changes would occur as a result of realising more uniform levels of reliability. This is one of the benefits of using reliability-based techniques in that more optimum use of material can be expected.

For the cases of loads and components not encompassed with LRFD, or where new data subsequently appear in relation to loads and components already covered by LRFD, the PRAC committee derived a procedure for determining the relevant factors.[4] The factors are presented in tabular form and are a function of the corresponding uncertainty, expressed in COV terms, and whether the load or resistance formulation relates to the mean or the 95% fractile value. Bias is accounted for by multiplying the factor obtained from the tables related to the bias. The procedure assumes typical ranges of environmental to gravity load ratios will be present and that the relevant distributions are log-normal.

Table VI: Comparison of RP2A and LRFD safety factors under independent load actions

Component	Load	RP2A	LRFD	Difference
Short column	Dead	1.67	1.53	–8.4%
	Live	1.67	1.76	+5.4%
	Environmental	1.25	1.59	+27.2%
Medium-length column	Dead	1.87	1.53	–18.2%
	Live	1.87	1.76	–5.9%
	Environmental	1.40	1.59	+13.6%
Tension member	Dead	1.67	1.37	–18.0%
	Live	1.67	1.58	–5.4%
	Environmental	1.25	1.42	+13.6%

Table VII: Number of extreme utilisation ratios in excess of unity

Platform	RP2A	LRFD
A	2	6
B	0	2
C	2	9
D	0	11

Platforms A–C subjected to static analysis, D to dynamic analysis.

Table VIII: Comparison of LRFD specified and estimated factors

Component	Specified factor	Estimated factor
Dead load	1.3	1.23
Live load	1.5	1.31
Environmental load	1.35	1.39
Tension yield	0.95	0.80
Compression	0.85	0.80
Bending	0.95	0.94
Hydrostatic	0.80	0.80
T, Y, DT joints – Compression	0.95	0.87
T, Y, DT joints – Tension	0.90	0.59*
K joints – Axial	0.95	0.86
– IPB	0.95	0.95
– OPB	0.95	0.90
Piles	0.80	0.67

* obtained by extrapolation.

Table VIII presents a comparison of the load and resistance factors as specified in LRFD and as obtained by the alternative provisions. In half the cases the two values are seen to more or less coincide. In the others, not insignificant differences occur. These have been acknowledged in the PRAC reports and the specific factors substantiated as discussed in the following paragraphs.

Deck legs are dominated by dead and live loads and frequently demonstrate no redistribution capability, since few if any alternative load paths are provided in the event of one leg failing. This relatively low level of 'unquantified' safety, and the absence of a systems factor to reflect redundancy, led to the adoption of 1.3 and 1.5 as the relevant factors for dead and live loading when gravity loads dominate.

In the case of tension yield, although 0.95 appears too high, it was justified on the grounds that:

1. tension failure is not necessarily catastrophic in that strain hardening is usually available;

Table IX: Implications of North Sea conditions on LRFD load factors

North Sea conditions	Basis of assessment	Present load factor	North Sea load factor
Environmental load bias 0.85 COV 0.23	Tabulated approach for loads outside scope of LRFD.	1.35	1.29
	Equation 3 (typical column in both cases)	1.35	1.23
Dynamic instead of static yield stress for extreme conditions	Columns to LRFD are of adequate reliability	1.35	1.27
Gravity loads	Columns under operational conditions with b increased by unity to allow for lack of redundancyin deck legs	1.23 1.31 (values from Table VIII)	1.46 1.61

2. test data are scarce so the bias was based on material bias and probably underestimates the real value. (In Ref 8, a modelling uncertainty parameter bias of 1.16 was obtained, in relation to tension plus pressure loaded ring stiffened cylinders, which was attributed to the difficulty of identifying failure in circumstances where instability (buckling) did not occur and strain hardening was likely to influence the observed failure capacity);
3. tension failure is ductile compared with buckling (in compression), so a lower level of reliability is acceptable compared with that associated with buckling (see Table V).

For tubular joints in general, lower resistance factors did not seem justified because:

1. any change in the relative values of joint reliability indices compared with member indices is not sustainable without consideration of economic and system factors, which was beyond the scope of the PRAC work;
2. greater differences in reliability were realised with the introduction of the revised form of checking equations, in place of the RP2A punching shear design procedure, than in converting the revised equations to LRFD.

In the case of tension loaded T, Y, DT joints, there was the additional difficulty in defining failure – first crack formation – which may not correspond to true ultimate strength. This led to the adjustment of safety levels in this case towards the LRFD average level, but not completely.

For piles, the difficulty in identifying an accurate soils model on which to base the assessment has not helped. Nevertheless, the lack of evidence to suggest present practice is unacceptable encourages the continuance of the use of RP2A reliability levels.

North Sea

A joint industry project is currently in progress which will examine the implications for North Sea designs of adopting LRFD. In addition it will use this information as the basis for deriving revised load and resistance factors which reflect the differences in environmental conditions, engineering practices and requirements that exist between the Gulf of Mexico/West Coast and the North Sea. At this stage of the project it is premature to quantify these implications in detail but some preliminary studies have been conducted which point to the extent of changes that might arise.

In relation to extreme environmental loading Ref 9 suggests, without substantiation, that the statistics for extreme environmental conditions in the North Sea are bias = 0.85 and COV = 0.23. These are to be compared with the equivalent Gulf of Mexico values of 0.7 and 0.37 (see Table IV). The effect of introducing the North Sea values on the recommended load factor can be evaluated in two ways. Firstly, in accordance with the tabulated approach for determining load and resistance factors outside the scope of LRFD, which provided the estimated values in Table VIII. Secondly, *via* equation 3 assuming a typical column under extreme environmental loading only. The results of these evaluations are summarised in Table IX from which it can be seen that the equivalent North Sea load factor might lie close to that presently used as the minimum RP2A value of 1.25.

The LRFD evaluation involved a yield stress bias corresponding to testing at slow strain rates. Only under gravity loading could it be argued that very slow (static) strain rates are relevant. For the periods associated with extreme waves, some 16s, dynamic yield stresses are probably more appropriate. The ratio of dynamic to static yield stress is possibly at least 1.06, but can be as high as 1.13 according to RP2A, 12th edition. Assuming the present LRFD column reliability to be adequate, using a dynamic value of yield stress in the evaluation of a revised load factor, *via* equation 3, leads to 1.27 as the appropriate extreme environmental factor (see Table IX).

Table VIII demonstrated the consequences for dead and live load factors of assuming average reliability under extreme environmental conditions was also relevant for gravity load dominated situations. It was then indicated that it was the concern for deck legs and their lack of redundancy which led to the adoption (ie without calibration) of dead and live load factors not insignificantly greater than these 'rational' factors. An alternative approach to the derivation of operational dead and live load factors is to introduce increased safety demands when alternative load paths are not available. For example in Ref 10, it was demonstrated that the effect of redundancy in relation to a well-braced four leg jacket was to raise fully utilised column reliability indices from 1.83 to 3.06. If *via* equation 3, the β implicit for columns under dead and live loads are increased by unity, for example, the corresponding load factors become 1.46 and 1.61 (see Table IX). These are in excess of the present LRFD factors and could of course be refined. Nevertheless, this approach provides an alternative strategy for deriving load factors for components for which redundancy is not available to provide alternative load paths in the event of a failure.

ADVANTAGES OF LRFD

The advantages of adopting a limit state approach to structural design in place of the traditional 'safety factor' technique are many. A number of these are summarised in the following paragraphs.

1. It encourages the use of mean value strength formulations, which by their very nature are improved representations

of physical behaviour, rather than upper or lower bounds or any other characteristic values.
2. As mean value formulations, they are less affected by the vagaries of experimental techniques and procedures.
3. It provides a rational measure of structural safety which the traditional safety factor approach cannot emulate and thus provides a sound basis for promoting designs in 'frontier' areas.
4. It allows the demands of safety versus economy to be optimised thus leading to more efficient use of material.
5. Nearly equal consideration has to be given to both strength and load modelling, a demand not apparent with traditional design approaches.
6. The techniques used (structural reliability analysis) can generally quantify the sensitivity of the system under consideration to each of the basic variables which, when ordered, enable rational decisions concerning research needs to be made.

CONCLUSION

The API RP2A-LRFD draft has been reviewed. It represents the culmination of a substantial effort which has involved a thorough evaluation of the load and resistance modelling inherent in the most widely used guide to fixed offshore platform design. These efforts in modelling have led to a significant number of improvements in designs to RP2A and have helped to pinpoint areas where data are scarce, or non-existent, and have thus provided a firm basis for decisions concerning research needs.

In implementing the results of the studies, care has been exercised to maintain a balance between present practice and the demands of a fully rational solution. This has been essential to avoid interfering with the basis of engineering judgement and experience.

The scope of the studies has guaranteed that RP2A-LRFD represents a sound basis for fixed offshore platform design in the 1990s. A framework has been provided by which the document can be implemented in different environmental regions of the world while also accounting for differences in engineering practice. As such RP2A-LRFD is a step forward so that, following local adaptation and implementation, designers of North Sea platforms and of those in other regions of the world can look forward with confidence to the continued use of a document with which they are thoroughly conversant, knowing that it will produce designs more optimised with respect to safety and economy than has been possible in the past, and that such designs can be installed in the frontier areas, such as deep waters and earthquake regions, which are presently challenging engineering skills.

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