

TUBULAR STRENGTH COMPARISON OF OFFSHORE JACKET STRUCTURES UNDER API RP2A AND ISO 19902

(Date received:6.8.10/Date approved:28.5.11)

Arazi B. Idrus¹, Narayanan Sambu Potty² and Zafarullah Nizamani³

^{1,2}Associate Professor, ²PhD Student

^{1,2,3}Department of Civil Engineering, Universiti Teknologi PETRONAS
Bandar Seri Iskandar, 31750 Tronoh, Perak Darul Ridzuan

Email: ¹arazi_idrus@petronas.com.my

ABSTRACT

Offshore jacket platforms in Malaysia are designed using API RP2A Working Stress Design (WSD) code. WSD code has proved its effectiveness and has been in use for long time, but it needs to be changed into Load and Resistance Factor Design (LRFD) based code which is being followed by all building code agencies. In WSD, design safety factor is provided only on resistance side and is based on judgement and experience. In place of WSD, Limit State Design or LRFD has proved to be more rational as it is based on probabilistic models. The reliability of jacket platforms is maintained in API RP2A LRFD by setting target safety factor the same as that provided in WSD designs, which means structures designed as per LRFD code will have the same reliability as API RP2A WSD (which has already provided safe structures and the best available practice for design). When adopting LRFD methodology, the appropriate load and resistance factors can be optimised through the process of calibration. Knowledge of the strength equations in the different codes and the similarities and differences between them is useful for the calibration. The first step in the calibration process is the determination of reliability of structural tubular members of the jacket designed as per existing practice of WSD and LRFD code. Here in this research, API RP2A WSD code and International Standard Organization (ISO 19902) (LRFD based code) are taken into consideration for the reliability analysis. In this paper, the relevant strength equations of three codes are identified and compared and the similarities and differences are determined for tubular members which are the main part of jacket structures.

Keywords: APIWSD, ISO 19902, Offshore Jacket Platform, Tubular Member Stresses

1. INTRODUCTION

Offshore Jacket Platforms are normally designed using one of the following offshore design codes: API RP2A WSD [1], API RP2A LRFD [2] or ISO 19902 [3]. Locally, Malaysia has its version of the code i.e. PETRONAS Technical Standards (PTS) [4], which is actually based on the API RP2A WSD. The aim of this paper is to determine the similarities and differences in resistance formulations provided in codes of API RP2A WSD, LRFD and ISO. Nine types of stresses are chosen for comparing the design resistance formulae i.e. Axial tension, Axial compression, Bending, Shear, Hydrostatic pressure, Tension and bending, Compression and bending, Tension, bending and hydrostatic pressure and Compression, bending and hydrostatic pressure.

API RP2A-LRFD and ISO 19902 codes are limit state design based approaches for design of steel jacket platforms. API WSD uses a common factor of safety for material where as in API LRFD and ISO factors are constant in value for the type of resistance under consideration. The growth of design codes is an indicator of development of structural design since the codes; reflect engineering practice [5]. In this paper the tubular member design equations in three codes are considered and main similarities and differences among them are identified. The equations for tubular members in

all the above codes are based on theory of shell buckling. Important dissimilarities are there in the equation for axial compression especially with regard to local buckling and some load interaction equations. The overall column buckling equation used in API WSD is same as the equation in API RP2A LRFD and ISO-19902 but has different coefficients; here ISO gives lower capacity compared to LRFD. The interaction equation for tension/compression along with bending in ISO follows the API WSD and is linear but the LRFD equation has a cosine form. For the numerical comparisons, tubular members of different diameters, thickness and lengths are chosen from an earlier analysis and axial, bending and hoop strengths evaluated and compared.

This paper reviews and summarises the comparison of the three basic codes for offshore jacket platforms and provide in detail the tubular member resistance. The load factors used in API RP2A LRFD and ISO are discussed along with inherent safety factor present in API RP2A WSD. Resistance formulae for the nine main stress conditions are chosen for evaluation and their strengths and weaknesses are compared. Here the steel tubular member structural components primary members are chosen which sustain the dead, live and environment load coming on the main structure. LRFD and ISO standards are based on limit state approaches which uses

the partial safety factors (for loads), multiplied with, characteristic loads to give design action effects, and partial safety factors multiplied with characteristic resistances to give design resistances. The WSD is allowable strength design approach whereas ISO and LRFD use factors which are constant in value for the type of resistance under consideration.

2.0 BACKGROUND

The first design standard for offshore structures, the API WSD, was published in October 1969. The 21st edition of API RP 2A WSD was published in 2000. After judging the advantages of LRFD in AISC [7] it was considered that the time was ripe to have an API RP2A LRFD code which was ultimately published in 1993. The industry initially applied the WSD codes in international locations. The expansion of national standards and globalisation of major projects/resulted in a desire for an international standard. The oil and gas industry, the Exploration and Production Forum and the API identified the International Organisation for Standardisation (ISO) as the entity to do this [8]. The ISO Technical Committee 67 was set up with 7 Sub-Committees. SC 7 addressed Offshore Structures [9]. This was followed by an international code/standard in 1998 with ISO 13819 [10] which has now been modified in ISO 19902 in 2007. In the development of the ISO, the base document is the API RP2A LRFD [11].

The member resistance formulae in WSD have undergone major changes three times [5]. The member resistance formulae were introduced in the 6th edition in 1975. Prior to this, WSD recommended the use of AISC provisions. The 1975 edition provided guidance on local buckling, hydrostatic pressure, interaction formulae for axial compression, bending stress, axial tension and hoop stress. The 11th edition (1980), equations were introduced for allowable hoop stress, a formula for combined effects of axial compression, bending and hydrostatic pressure. The 17th edition (1987), the allowable bending stress was increased from 0.66fy to 0.75fy for members not susceptible to local buckling. The 1993, when the LRFD version was introduced, some formulae were modified. This was incorporated in the 21st edition of WSD.

This work is a part of the ongoing work at the Universiti Teknologi PETRONAS to determine the load and resistance factor for design of jacket platform in Malaysia.

3.0 LITERATURE REVIEW

All the three codes which are compared provide equations for single load case as well as for combination of loads. Chord and bracing members of jacket platforms suffer from combined stresses due to wave and current forces. Gravity loads dominate the leg member design but environmental loads dominate the design of brace members [13]. In API working stress design method, the allowable stresses are either expressed implicitly as a fraction of yield stress or buckling stress, or by applying a safety factor on the critical buckling stress [14]. In-place extreme environmental design conditions for the ultimate limit state or buckling failure modes is considered. For buckling this is often the governing design condition for majority of structural components in offshore platforms. [14]. Utilisation ratio is equal to modelling uncertainty (experimental strength to predicted strength) [14]. The expressions for utilisation ratio are explicitly provided in the ISO but not in WSD and LRFD. Local buckling checks are required to be made

for members with D/t >60 in all codes [14]. Bracing members act as ties or struts depending on whether they carry tensile or compressive loading [14]. Chord and brace members have to withstand hydrostatic pressure and bending moment which arise due to wave and current forces and from load redistribution at the nodal points [14].

For thick walled tubular members, (d/T < 60) the strength of very stocky columns reaches full yield even at the characteristic level due to strain hardening. At large slenderness (λ) API curve is similar to Euler buckling curve but ISO curve lies 10% below it. Greater differences are observed for thin walled tubulars (D/t = 120). The difference between API LRFD and ISO is maximum, when thin walled column, is short (low λ) [10]. API LRFD and WSD load capacities have been compared to ISO with all resistance and load factors included with environmental to gravity load ratio is 2 to 4 [15]. The LRFD curve for smaller D/t ratio starts at unity and moves upward to 1.11 (1/0.9), this shows LRFD has more capacity than ISO [15]. At greater D/t ratio LRFD crosses the unity line, short columns of ISO shows more capacity than LRFD but less at higher slenderness while API WSD curves lies constantly above ISO and LRFD specially for greater live to dead load ratios [15].

There is great difference between API and ISO for local buckling. In ISO formula, the material properties as well as the geometric properties influence the local buckling [15]. ISO and API LRFD provisions for hydrostatic pressure are identical but different for WSD. The pressure which can be sustained is directly proportional to tubulars are nominally stronger according to ISO or API LRFD over the range where elastic buckling stress lies between 0.55 and 6.2 times yield stress [15]. LRFD and ISO remain near WSD when partial load and resistance factors are considered.

However WSD safety factor is 1.5 and ISO / LRFD load and resistance factors are 1.3 and 1.25 respectively. Thus the overall factors is 1.5 / (1.3 x 1.25) = 0.92 on the ISO / LRFD capacity relative to WSD [15]. Comparing the equations for combined loads, the ISO has utilised the simpler interaction equations of WSD which are linear whereas the API LRFD uses a cosine interaction equation [15]. The D/t ratio of a pile shall be small so that local buckling is avoided at stresses up to yield strength. API WSD/ LRFD give minimum pile wall thickness, where continued hard driving of 820 blows per meter with biggest size hammer is used which is, $t = 6.35 + D/100$. The API values for pile diameter and thickness varies between (610-3048 mm) to (13-37) respectively [16].

The minimum annulus (gap between pile and the sleeve) recommended by RP2A WSD and RP2A LRFD is 38 mm while the ISO recommends an annulus of 40mm [17]. In ISO wind actions on downstream components can be reduced due to shielding by upstream components. For perpendicular wind approach angles with respect to projected area, API provides common shape factor coefficient for cylindrical members whereas ISO divides cylindrical members into four classes [18] as shown in Table 1.

Table 1: Shape coefficients

Component		Shape coefficients (C _s)	
		WSD/ LRFD	ISO
Cylinders	Smooth, $R_e > 5 \times 10^5$	0.5	0.65
	Smooth, $R_e \leq 5 \times 10^5$	0.5	1.20
	Rough, all R_e	0.5	1.05
	Covered with ice, all R_e	0.5	1.20

In ISO the minimum capacity for joint requirement is only for primary or significant joints which influence reserve system strength (critical load paths) or secondary joints whose failure has important safety or environmental effects [19].

4.0 METHODOLOGY

This study compares the resistance formulae for different stress conditions in API RP2A WSD, API RP2A LRFD and ISO 19902 and the corresponding safety factors, these equations play a very vital role in finding the resistance factors for jacket platforms in Malaysia as randomness and uncertainties are accurately accounted [20-24]. The similarities between the codes are identified. Where there are differences, the source of the formula is identified. The limiting conditions for the use of the formulae provided by the different codes are also discussed.

The structure contains uncertainty and randomness in itself i.e. material resistance, geometric parameters, initial defects etc. There is uncertainty in the physical models used to assess load effects and response of structure [12,25]. The characteristic loads are multiplied with safety factors to give design load effects, and divisors are applied to characteristic resistances to give design resistance [6]. There are differences in ISO and LRFD equations for the different types of resistance.

The objective of this paper is to review the differences in stress equations provided in the three major codes for design of offshore jacket platforms. These stresses are evaluated numerically by putting values in the given equation and then comparing them. After comparison the differences are highlighted [26,27].

5.0 COMPARISON OF TUBULAR STRENGTH EQUATIONS IN DIFFERENT CODES

Jacket platform component failures include brace buckling, plastification of the section, and punching of a chord by a brace [12]. Geometric slenderness D/t is limited in ISO up to 120 and material yield strength is limited to 500 MPa (taking lead from NORSOK code) (Table 2). Failure criteria may be expressed as an interaction equation among member internal action and resistance variable.

The parameters for tubular members are yield stress, strain hardening, Young's modulus, residual stresses, section parameters (diameter and thickness), out of roundness of the section and out of straightness of the member [12]. Comparing API LRFD and ISO, the average reduction in combined axial tension and bending capacity of ISO was observed to be 9%; for axial compression, bending and pressure, the average reduction in ISO was found to be 7%; while for combined tension, bending and pressure, the ISO formulation showed increase of capacities of 10% [13].

Table 2: Limit values for the variables in the three codes

Item	API-WSD	API-LRFD	ISO 19902
Wall thickness of member	≥ 6mm	≥ 6mm	≥ 6mm
D/t	<120*	<120*	<120
Yield Strength	<414 MPa	<414MPa	<500 MPa
Yield strength to ultimate strength	–	–	0.85
Yield strength to ultimate tensile strength ratio	–	–	< 0.9

* In the local buckling equations used for axial compression, bending and hydrostatic pressure, D/t <300 is acceptable.

5.1 Axial Tension

The allowable axial tension is taken as 0.6F_y. This is based on AISC and has remained unchanged from 1969 [5]. The LRFD and ISO expressions are identical. Due to low consequences of tension yielding, safety indices in ISO and LRFD for extreme loading is taken larger than used in WSD. The equations in LRFD and ISO are used for yielding of gross section of cylindrical members which covers vast majority of structures related to offshore engineering, where as for non tubular members the analyses is made through AISC LRFD / WSD equations respectively. In comparing design resistance with respect to partial safety factor, the ISO design resistance is 0.95/0.952= 99.75% of API LRFD resistance. Thus the expressions are the same. This kind of stress, acting independently as a governing stress, occurs very rarely for offshore structures as shown in Table 3.

Table 3: Comparison of axial tension equation

API RP2A-WSD	API RP2A-LRFD	ISO 19902
$F_t = 0.6 * F_y$ $F_t = \text{tensile stress}$ Safety factor = 0.6	$f_t = \phi_t * F_y$ $f_t = \text{tensile stress}$ $\phi_t = 0.95$ Safety factor = 0.95	$\sigma_t = \frac{f_t}{Y_t}$ $\sigma_t = \text{tensile stress}$ $f_t = \text{tensile strength} = f_y$ $\gamma_t = 1.05$ (Safety factor = 0.9524)

F_y = Yield strength

For comparison of equations the safety factors have to be removed from above equations so that they will be at par with each other. Thus they can be written as in Table 4.

Table 4: Comparison of axial tension equation without factors

API RP2A-WSD	API RP2A-LRFD	ISO 19902
$F_t = F_y$	$f_t = F_y$	$\sigma_t = f_y$

5.2 Axial Compression

LRFD takes 0.85 as safety factor, where as ISO takes 1.18 as a factor but both becomes equal when put in respective equations. Low D/t ratio members are not subject to local buckling under axial compression and API recommends that unstiffened tubular members should be investigated for local buckling, when D/t ratio is greater than the limiting value.

Unstiffened tubular members under axial compression have following failure modes [5].

- i) Material yield
- ii) Euler column (overall) buckling
- iii) Local buckling
- iv) Combination of all

5.2.1 Overall Column Buckling

Characteristic column strength is normalised with respect to the tubular yield stress, when partial safety factor is unity, for API RP2A- LRFD and ISO 19902. The overall column buckling equation used in API WSD is adopted from AISC and is not similar to API LRFD or ISO. Equations provided in LRFD and ISO are similar in form but different coefficients are used. Here the capacity of ISO equation is lower than LRFD equation [15]. API WSD column strengths cannot be compared at a characteristic

level because of working stress design system. But total unfactored load capacities can be compared.

In Figure 1, LRFD and WSD loads are compared to ISO loads, with all resistance and load partial factors included in the computation [15]. The load capacities are dependent on assumed environmental to gravity load ratio with a range of 2-4 has been shown [15]. As partial load factors for API LRFD and ISO are same, LRFD curves are same in all graphs [15]. The dark LRFD curve starts at unity and climbs to 1.11 (= 1/0.9) and this shows that LRFD will give more capacity than ISO [15]. The LRFD thin curve crosses the unity line, the short columns ISO gives greater capacity than LRFD but less at higher slenderness. The API WSD curves consistently lie above both ISO and LRFD and for higher in Figure 1, LRFD and WSD loads are compared to ISO loads, with all resistance and load partial factors included in the computation [15]. The load capacities are dependent on assumed environmental to gravity load ratio with a range of 2-4 has been shown [15]. As partial load factors for API LRFD and ISO are same, LRFD curves are same in all graphs [15]. The dark LRFD curve starts at unity and climbs to 1.11 (=1/0.9) and this shows that LRFD will give more capacity than ISO [15]. The LRFD thin curve crosses the unity line, the short columns ISO gives greater capacity than LRFD but less at higher slenderness. The API WSD curves consistently lie above both ISO and LRFD and for higher live/dead load ratios.

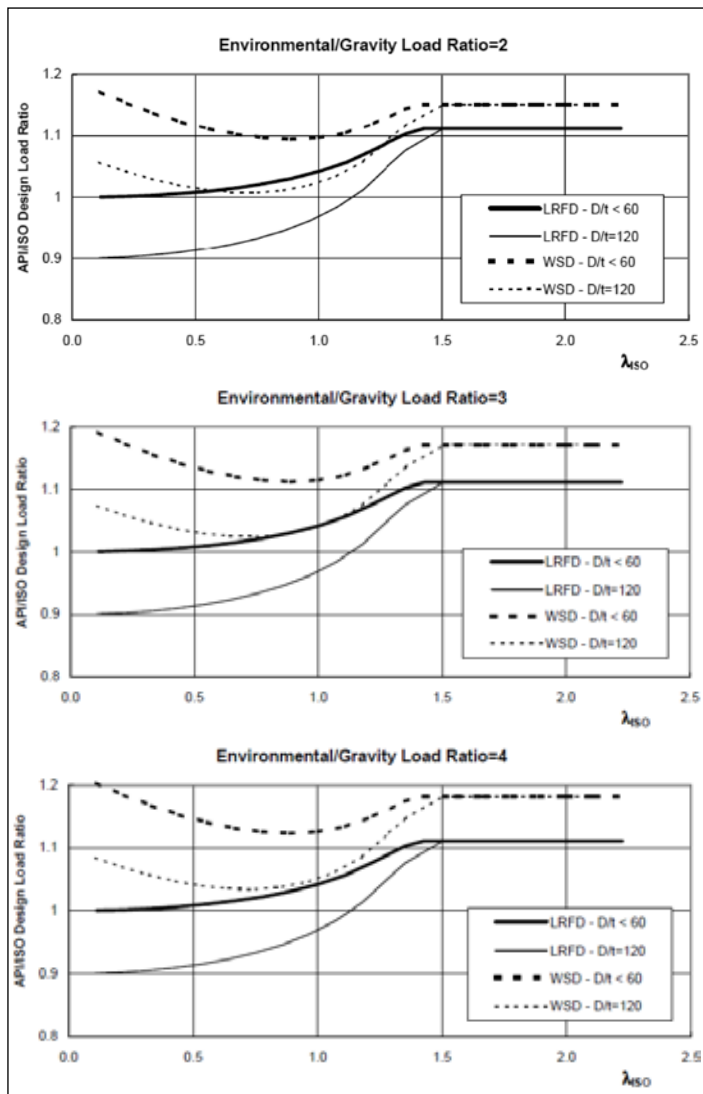


Figure 1: Ratio of API (LRFD and WSD) column strength to ISO column strength [10]

Over all column buckling: The WSD formula is based on the AISC [7]. The expressions in LRFD and ISO are similar, there being a difference in the constant in the expressions (0.25 in LRFD and 0.278 in ISO). Also the limiting value for λ is √2 in LRFD and 1.34 in ISO. There is also a small variation in the expressions for λ > √2 or 1.34 where the ISO expressions is factored using 0.9.

Cylindrical shells with low D/t ratio are not prone to local buckling under axial compression and are designed on the basis of material failure i.e. local buckling stress is taken same as yield stress, but as compared to this high D/t cylindrical shell must be checked for local shell buckling. In its commentary Clause 13.2.3.2, ISO gives separate equation for a member composed of two or more separate cross-section along member length how ever there is no provision mentioned in API codes. The axial compressive strength is determined as follows:

- i) Find elastic buckling strength P_{e} for whole member taking into consideration end restraints and variable cross-sectional properties.
- ii) Find effective length factor of member
- iii) The axial compressive strength $P_{c,r}$ is determined by:

$$P_{c,x} = [1 - 0.278 \frac{P_{yc,x}}{P_e}] P_{yc,r} \text{ for } (\frac{P_{yc,r}}{P_e})^{0.5} \leq 1.34 \quad (1)$$

$$P_{c,r} = 0.9P_e \text{ for } (\frac{P_{yc,r}}{P_e})^{0.5} > 1.34 \quad (2)$$

The axial compressive stress of each section is acquired by dividing $P_{c,r}$ by the respective cross-sectional area A_i .

In Figure 2 characteristic column strength is normalised with the yield stress of cylindrical member (without partial safety factor). This normalised strength is plotted against the column slenderness (λ). From this it is clear that LRFD equation match with Euler buckling curve for λ ≥ √2, when D/t > 60. Few strength equations ever match with their elastic critical buckling curves, for values of nondimensional slenderness quite near to unity [13]. Here slenderness is related to critical stress, which the cylindrical member can uphold without local buckling. For thick cross-section columns, this critical stress is the yield stress and thus here λ for ISO and LRFD is equal, which makes LRFD and ISO strength points fall on same vertical line [15]. Thin walled cylindrical member subject to local buckling will have displaced points because of different equations used in different codes.

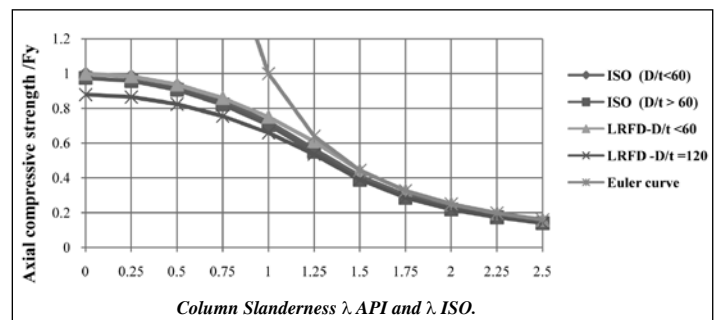


Figure 2: Comparison of characteristic column curve strength of ISO 19902 and API LRFD

5.2.2 Local buckling

Circular members with low D/t ratio are not subject to local buckling under axial compression and are designed with respect to material failure (local buckling stress is taken equal to yield stress). But as D/t ratio increases, elastic buckling strength decreases, and now member should be checked for local buckling.

5.2.3 Elastic buckling

Unstiffened thin walled cylinders under axial compression and bending can fail at loads below buckling loads as predicted by small deflection shell theory and there is sudden drop in load carrying capacity upon buckling. This buckling load is also affected along with geometric imperfections by boundary conditions and residual stresses, which cause inelastic action to commence before nominal stresses due to applied loads reach yield strength. Local buckling should be checked whenever $d/t > 60$, $d/t = 60$ is suitable for commonly used offshore platform steel $F_y = 242$ MPa to 414 MPa (35 to 60 Ksi). The expressions for local buckling in WSD and LRFD are identical for $D/t \leq 60$ and also $D/t > 60$. Note that the limits given are geometrical limits. The expression in ISO is similar to the NORSOK [6] and dependent on material factor limits.

5.2.4 Inelastic buckling

Offshore cylindrical members as per LRFD fall in to the inelastic range normally [3]. Inelastic local buckling as compared to elastic buckling can be taken as less sensitive to geometric imperfections and residual stresses.

5.2.5 Effective length factor (K)

Effective length factor of bracing member is reduced in ISO code [27]. Clause 3.3.1.d of API RP2A WSD, clause D3.2.3 of LRFD and clause 13.5 of ISO provides the effective length factor and moment reduction factors for different members, which is reproduced in Tables 5 and 6 respectively.

Table 5: Effective Length factor (K)

Structural component	RP2A WSD	RP2A LRFD	ISO 19902
Topside legs			
Braced	1	1	1
Portal (unbraced)	See note	See note	See note
Structure legs and piling			
Grouted composite section	1	1	1
UngROUTED legs	1	1	1
UngROUTED piling between shim points			
Structure brace members			
Primary diagonals and horizontals K-braces	0.8	0.8	0.7
x-braces	0.8	0.8	0.7
longer segment length full length -	0.9	0.9	0.8
	-	-	0.7
Secondary horizontals	0.7	0.7	0.7

Note: The Effective Length Alignment Chart provided in all three codes is to be used. The alignment charts are provided in AISC and section A 13.5 of the ISO.

The effective length is found by a rational analysis considering joint restraints, joint flexibility and joint movement. Studies indicate that buckling lengths determined from refined analysis improved design predictions [28]. Studies on X-frame have been done by Livesley [14] and Knapp and Dixon [29] and API follows the AISC effective Length Alignment Charts where as

ISO has its values presented through its commentary clause A.13.5. The length to which the effective length factor is applied is normally measured from centreline to centreline of the end joints. For members framing into legs two cases are: (a) face of leg to face of leg for main diagonal braces, (b) face of leg to centreline of end joint for K-braces. C_m is used to obtain an equivalent moment for the moment pattern to which a beam-column is subjected to.

Table 6: Moment reduction factors

Structural component	RP2A WSD	RP2A LRFD	ISO 19902
Topside legs			
Braced	0.85	1	0.85
Portal (unbraced)	0.85	0.85	0.85
Structure legs and Piling			
Grouted composite section	C	1	C
UngROUTED legs	B	1	B
UngROUTED piling between shim points			
Structure brace members			
Primary diagonals and horizontals K-braces	B OR C	0.8	B OR C
x-braces	C	0.8	B OR C
longer segment length full length	C	0.9	B OR C
		-	B OR C
Secondary horizontals	C	0.7	B OR C

Where,

$B = 0.6 - 0.4 (M1/M2)$, but not less than 0.4, not more than 0.85
 $C = 1 - 0.4 (fa/Fe')$, or 0.85, whichever is less.

Figure 3 compares local buckling strengths, normalised with respect to yield stress, as a function of cylindrical slenderness (D/t). API equation provide single curve, which is independent of yield stress, where as ISO equation provide different curves related with yield stress. Aside from relatively small region near $D/t = 60$ and for higher strength steels, lower buckling strengths are shown by API.

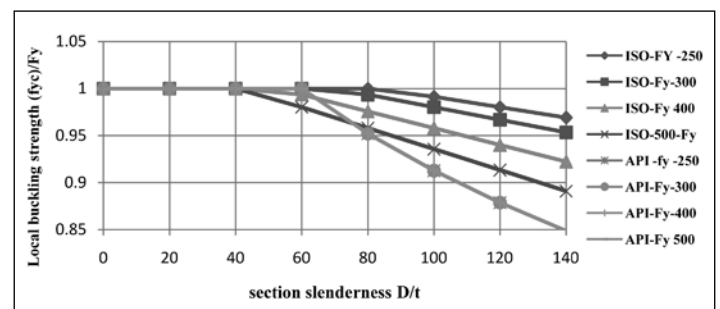


Figure 3: Comparison of API and ISO local buckling strength

Figure 4 shows the ratio of API local buckling strength to that of ISO. This ratio applies to very stocky but short columns, for long columns overall buckling starts first and thus local buckling effects are not significant.

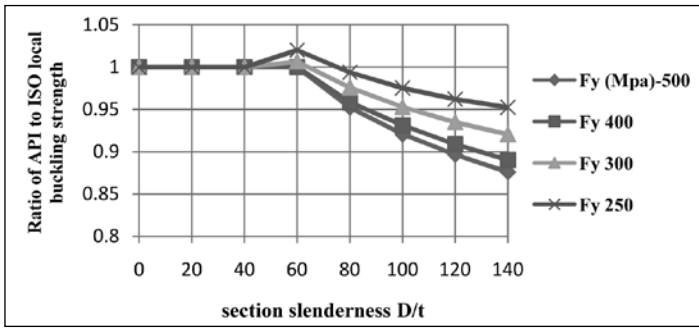


Figure 4: Comparison of ISO and API (LRFD or WSD) local buckling strengths

Figure 5 shows that for $D/t = 60$, and yield stresses in excess of 350 N/mm^2 , the ISO provision is more burdensome than LRFD, whereas in yield buckling interaction region ($D/t \geq 60$), the ISO equation is more optimistic than LRFD

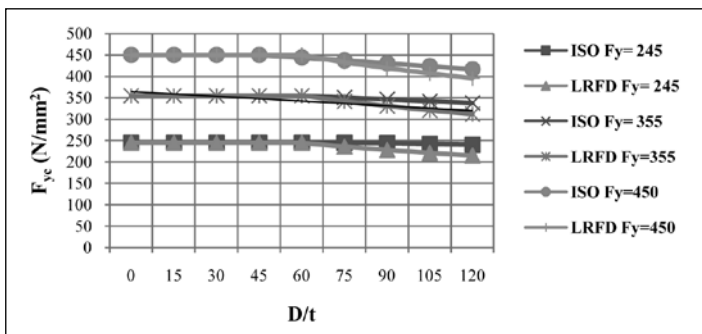


Figure 5: Comparison of API and ISO local buckling strength

Figure 6 shows that,

- i) ISO is independent of yield stress, but LRFD provides different requirements for different values of yield stress. This should not occur in non-dimensional structural strength frame.
- ii) ISO gives more structural efficiency in comparison to LRFD.

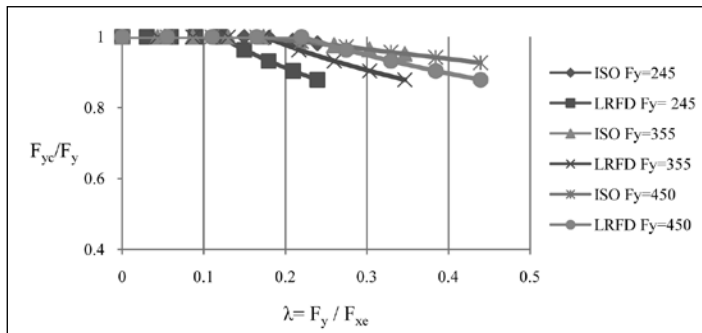


Figure 6: Comparison of API and ISO local buckling strength

5.3 Bending

For $D/t \leq 10340/f_y$, the bending strength formula for WSD is $0.75f_y$. In comparing design resistance formulae with respect to partial safety factor, the ISO design resistance is $0.95 / (1/1.05) = 100\%$ of API LRFD resistance. The expressions are the same. The limits given in WSD and LRFD are geometric (D/t) whereas the limits used in ISO are having material strength and Young's modulus. The upper limit for D/t given in WSD and LRFD is 300. Failure of cylindrical members in pure bending is precipitated by localised axis symmetric bulges on the compression side of the cylinders [10]. Like local buckling (in axial compression) buckling behaviour depends on D/t ratio, at larger D/t ratios both

moment and rotational capacities of tube decrease. Tubular members of jacket may have bending stresses due to any of following three material regions:

- a) Inelastic,
- b) elastic to plastic,
- c) elastic

As per API LRFD Simply supported beam tests have smaller moment capacities than fixed end beam tests. Reduction in moment capacity is considered with the reduction in support rigidity. On the other hand end conditions have little influence on rotational capacity of cylinder. At low $F_y d/t$, plastic hinge mechanism forms over short length of tubular. Now when end support rigidity is reduced, hinge is formed over a longer segment of cylinder. $F_y d/t$ for tubular shell increases where as moment as well as rotational capacities decreases. Behaviour of cylindrical shell is defined, when behaviour of cylinder subjected to bending is separated into three regions:

- a) High rotational capacity: Ductile failure mode *i.e.* load decay is gradual
- b) Intermediate rotational capacity: Semi ductile failure mode *i.e.* load decay is even more gradual
- c) Low rotational capacity: Little post yield ductility *i.e.* Load decay is rapid and is susceptible to local buckling.

From above region (a) extending up to $F_y D/t = 10,340 \text{ MPa}$ allows to develop full plastic moment capacity. This is reduced to 10% in excess of yield moment capacity ($M_u/M_y = 1.10$) at $F_y D/t = 20,680 \text{ MPa}$ in region (b). LRFD nominal bending stress 'defines full plastic capacity of tubular section in region (a) while WSD formulation for allowable bending stress increased by (1.67- safety factor) yields less full plastic capacity [3]. In WSD allowable stresses for cylinders under bending have been derived by using a safety factor of 1.67 against ultimate bending capacities at lower bound. WSD and LRFD are based on same relationship with ultimate moment capacity normalised with respect to yield moment capacity (M_u/M_y).

In ISO bending strength of fabricated tubular members is achieved by dividing the ultimate plastic moment strength by elastic yield moment. Here ultimate bending moment strength is called full plastic moment of member. Members with $f_y = 345 \text{ MPa}$ and $E = 205000 \text{ MPa}$ full plastic moment can be developed if $D/t \leq 30$, when $D/t \approx 60$, the strength is linearly reduced to about 10% in excess of yield strength.

5.4 Shear

Two types of shear are identified namely the beam shear and torsional shear.

- a) Beam shear: The expressions in all the three codes are similar when the factors are removed. In the WSD, the allowable beam shear stress is taken as 0.4 times the yield strength. The representative shear strength is taken as $f_y/\sqrt{3} = 0.58f_y$ in ISO, the partial resistance factor being 1.05. In LRFD the resistance factor is 0.95 which is same as in ISO (*i.e.* $1/1.05 \approx 0.95$).
- b) Torsional shear: The expressions in all the three codes are similar when the factors are removed. In the WSD, the allowable torsional shear stress is taken as 0.4 times the yield strength. The partial resistance factor is 1.05 in the ISO. In LRFD the resistance factor is 0.95 which is same as in ISO

5.5 Hydrostatic pressure (Hoop buckling)

In WSD the design formula is given as $f_h \leq F_{hc} / SF$. For F_{hc} , expressions are given for four elastic stress ranges. In comparing design resistance formulae of ISO and LRFD with respect to partial safety factor, the ISO design resistance is $0.80/(1/1.25) = 100\%$ of API LRFD resistance. The expressions in LRFD and ISO are identical. However, LRFD provides only a single expression for critical hoop buckling whereas in ISO provides formula for 3 ranges of elastic hoop buckling strength. The expression for design hydrostatic head provided in WSD and LRFD are identical. The ISO formula is similar but however uses z with positive measured upwards. Same expressions are provided for circumferential stiffening ring design in WSD and LRFD.

However, the ISO gives additional guidance on (a) external and internal rings, (b) guidance for avoidance of local buckling of ring stiffeners with and without flanges. Hydrostatic buckling is an extremely dangerous failure mode and the safety indices are set in upper range (above 3) found from calibration of WSD. Hoop buckling occurs when tubular members subjected to external pressure. Hoop buckling stress is determined through:

- i) Material yield strength with respect to elastic hoop buckling stress.
- ii) Design equations are valid in the range of F

Along with hoop stresses, external hydrostatic pressure imposes a capped force in the member if ends are capped imposes hoop compression in tubular member and no capped-end compression.

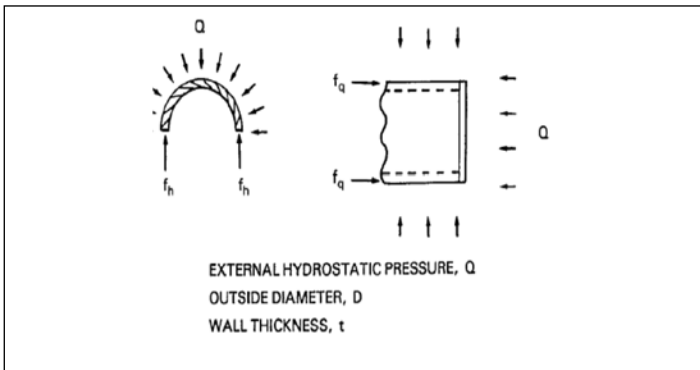


Figure 7: Hoop and capped end axial stresses resulting from external pressure [5]

As hoop and capped-end axial stresses from external assumed to have positive sign [5]. Un go through local buckling of shell wall anywhere between restraints. Effect of external pressure on circular member is magnified by an original end-circulars like braces, hydrostatic pressure also imposes an axial compressive stress of $0.5f$ some of which is taken by the structure and some of which passes into the member [10].

$$\text{Hoop stress} \leq \frac{\text{Critical hoop buckling capacity}}{\text{Hoop buckling safety factor}} \quad (3)$$

Critical hoop buckling capacity F_{hc} in API WSD is same as used in API LRFD (without resistance factor [5]). Elastic hoop buckling stress F_{he} is same in LRFD and ISO codes but critical hoop buckling stress F_{he} is different in WSD [27], which is shown in Figure 8.

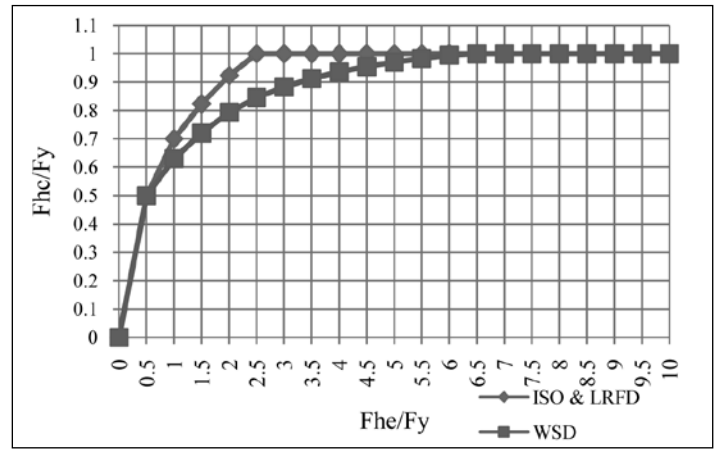


Figure 8: Hoop buckling strength as a function of elastic buckling stress

5.6 Combined stresses without hydrostatic pressure

Here circular members acted upon by combined axial as well as bending stresses are considered. The secondary moments from factored global stresses and bending stresses ($P-\Delta$) effects are not considered except in cases of large axial force or flexible component is under consideration. $P-\Delta$ effects are found to be important in the design of unbraced deck legs, piles, and laterally flexible structures [4].

5.6.1 Tension and bending

In WSD, the safety factor on axial component is 0.6 and for bending the allowable stress is determined from clause 3.2.3. The expression given in WSD in clause 3.3.2 is a modification of the expression AISC namely

$$\frac{f_a}{0.6F_y} + \frac{f_{bx}}{F_{bx}} + \frac{f_{by}}{F_{by}} \leq 1.0 \quad (4)$$

Equation 4 was modified for LRFD version where resistance factor comes into effect. In comparing the design resistance formulae with respect to partial safety factor, the LRFD has partial safety factors of $\phi_t = 0.95$ and $\phi_b = 0.95$, whereas ISO has $\gamma_{R,t} = 1.05$ and $\gamma_{R,b} = 1.05$. Hence the factors are identical. Here the components experiencing combined axial tension and bending actions are checked at all cross-sections along their length. If bending stress is greater than the axial tension, the local buckling effect (due to bending on compression side) is considered in bending strength (F_{bn}) [3]. The API LRFD interaction formula is in the cosine form. Neither API WSD nor ISO uses the cosine form. In API LRFD for the cosine equation, the largest interaction ratio from Equations D.2.1-1 and D.3.1-1 is to be used.

5.6.2 Compression and bending

The WSD equations are based on the AISC [5]. In WSD, two interaction equations have to be satisfied, one for member stability and one for plasticity. When axial component is small *i.e.* $f_a/F_a \leq 0.15$, an alternate formula is given. Also when different values of C_m and F_e are applicable for f_{bx} and f_{by} ; then formulae 3.3.1-4 can be used instead of formulae 3.3.1-1. Expression 3.3.1-4 is similar to expressions in LRFD and ISO without the partial factors. Expression 3.3.1-1 in WSD is identical to expressions in ISO. In comparing the design resistance formulae with respect to partial safety factor, the LRFD has partial safety factors of $\phi_c = 0.85$ and $\phi_b = 0.95$, whereas ISO has $\gamma_{R,c} = 1.18$ and $\gamma_{R,b} = 1.05$. Each standard uses two formulae *i.e.* one involving overall compressive

strength and $P-\delta$ amplified bending stress; and second involving local buckling strength and unamplified bending stress [13]. This type of stresses indicates beam-column nature of action of stress. Two equations are provided here first is for beam-column stability check and the second for strength check for components under combined axial compression and bending [4].

API-LRFD and ISO use AISC-ASD beam column stability interaction equation (first) and this gives conservative results when used for large scale offshore members where imperfections and residual stresses are comparatively more [LRFD code]. ISO also uses AISC [4]. Strength equation in ISO is of linear form as compared to LRFD which has cosine form. ISO equation is conservative for $D/t < 25$ compared with cosine of LRFD [4]. Comparisons for members, with more bending stresses show higher interaction ratios. Use of cosine equations are limited to short specimen ($L/D = 3$), so there is not much support to use this equation at present [4]. C_{mx} and C_{my} are the reduction factors which depend on support conditions of member, end moments and whether transverse loading is applied and their value lies between 0.4 and 1.0.

5.7 Combined stresses with hydrostatic pressure

Circular member under the water line is subjected to hydrostatic pressure if it has not been filled with water [4]. Flooding is allowed in hollow legs due to upending and placement and for pile installation [ISO]. Members filled with water under in-place conditions are subjected by hydrostatic pressure during launch and installation [4].

Hydrostatic pressure effects are taken into account when conducting member checks like axial compression of capped-end pressures [4]. When longitudinal tensile stresses due to axial tension and bending and hoop compressive stresses (collapse) due to hydrostatic pressure occurs simultaneously then the interaction equations are used [1].

Circular members subjected to hydrostatic pressure are checked against following [4]:

- Hoop buckling under hydrostatic pressure.
- Tensile yielding under combination of action effects (capped-end forces results in tension in member)
- Compression yielding and local buckling when combined action effects like due to capped-end forces producing compression in member
- Column buckling when force effects, excluding that coming from capped-end actions results in compression.

5.7.1 Tension, bending and hydrostatic pressure:

The title of this classification given in the clause 3.3.3 of the WSD "Axial tension and Hydrostatic Pressure" is misleading since it includes bending also. The equation in WSD is based on the Beltrami and Haigh maximum total strain energy theory for biaxial loading.

In comparing design resistance with respect to partial safety factor, the LRFD has partial safety factors of $\phi_t = 0.95$, $\phi_b = 0.95$ and $\phi_h = 0.80$ whereas ISO has $\gamma_{R,t} = 1.05$, $\gamma_{R,b} = 1.05$ and $\gamma_{R,h} = 1.25$. Outside hydrostatic pressure has three main effects in existence of tensile forces [4]:

- Decrease of axial tension due to capped-end axial compression.
- Decrease in axial tensile strength (f_t) caused by hoop compression, results in $f_{t,h}$
- Decrease of bending strength (f_b) caused by hoop compression results in $f_{b,h}$

Axial tension hydrostatic pressure interaction is similar to bending-hydrostatic pressure interaction [4].

5.7.2 Compression, bending and hydrostatic pressure:

The title in WSD "Axial compression and Hydrostatic Pressure" is misleading. There are three criteria to be satisfied. In comparing the design resistance formulae with respect to partial safety factor, the LRFD has partial safety factors of $\phi_t = 0.85$, $\phi_b = 0.95$ and $\phi_h = 0.80$ whereas ISO has $\gamma_{R,t} = 1.18$, $\gamma_{R,b} = 1.05$ and $\gamma_{R,h} = 1.25$. Capped-end axial compression due to hydrostatic pressure does not produce column buckling of a member under combined external compression as well as hydrostatic pressure. For stability check calculated axial compression *i.e.* external axial compression only is used.

6.0 CONCLUSIONS

The code equations for sufficiency of cylindrical members are almost similar for stresses acting independently or in group *e.g.* API RP2A WSD, LRFD and ISO have identical equations for axial tension, bending and hydrostatic pressure. The equations provided in the three codes for nine different stress conditions have been compared through descriptions and graphs. Some of the underlying factors for these differences were identified. These equations are valid for cylindrical members of offshore jacket platforms at all depths.

The following conclusions were drawn after comparing the three codes:

- ISO 19902 considers steel with yield stress up to 500 MPa where as in API Codes this limit is 414 MPa.
- Due to low consequences of tension yielding, safety indices in ISO and LRFD for extreme loading is taken larger than in WSD
- Effective length factor (K) of bracing member is 0.8 in API whereas it is 0.7 in ISO 19902 which shows the conservativeness of ISO.
- Local buckling check is based on only geometric parameter in API WSD and API LRFD whereas in ISO it depends on geometric and elastic modulus of members.
- Additional information is provided by ISO 19902 for external and internal rings and guidance for avoidance of local buckling of ring stiffeners with and without flanges
- In the local buckling equations used for axial compression, bending and hydrostatic pressure, the API allows the upper limit of D/t ratio up to 300 where as ISO 19902 permits up to 120 only.
- ISO 19902 gives separate equations when two or more separate cross-sections are combined in a member under compressive stress, unlike in the API codes.
- The bending stress equation in ISO contains modulus of elasticity and the yield strength, where as the API equation has only yield strength.
- Shear stress factors in API LRFD and ISO 19902 remain same, where as WSD has more reduced factors.
- Linear interaction equations are introduced in ISO following API RP2A WSD whereas cosine interaction equations are given by API LRFD.
- The criteria, for slender beam-column strength is made through reduction below elastic buckling.
- Capped end forces from hydrostatic pressure could be included in or excluded from analysis of jacket structures with subsequent strength formulations.

- m) In WSD, design formulae are provided for four elastic stress ranges. The equation in LRFD and ISO are identical. LRFD provides only a single equation for critical hoop buckling while ISO provides equation for three ranges of elastic hoop buckling strength.
- n) Members subjected to combined compression and flexure must be proportioned in such a way that they satisfy strength as well as stability criteria throughout their length.
- o) When design storm environmental conditions enforce stresses due to lateral and vertical forces WSD (AISC) stresses are increased by 1/3.

ACKNOWLEDGEMENTS

The authors thank Universiti Teknologi PETRONAS for supporting this project through its Graduate Assistantship scheme. ■

REFERENCES

- [1] API RP2A-WSD, 2000, 'Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design', 21st edition, American Petroleum Institute.
- [2] API RP2A-LRFD, 1993, 'Planning, Designing and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design', 1st edition, Reaffirmed May 16, 2003.
- [3] ISO 19902, Petroleum and Natural Gas Industries – fixed steel offshore structures, 2007
- [4] PTS 34.19.10.30, 2010, Design of Fixed Offshore Structures, PETRONAS Technical Standards, PETRONAS Carigalli Sdn Bhd.
- [5] Advanced Mechanics and Engineering Ltd., 1999, 'Assessment of the Historical Development of Fixed Offshore Structural Design codes', Offshore Technology Report, OTO 1999- 015. Prepared for HSE UK.
- [6] Bomel Ltd. For HSE, 'Comparison of Tubular Member Strength Provisions in Codes and Standards', Offshore Technology Report 2001/084
- [7] American Institute of Steel Construction (AISC), 1994, Manual of Steel Construction – Load and Resistance Factor Design.
- [8] Mangiavacchi, A., 2005, API Offshore Structures Standards: 2006 and Beyond, OTC 17698, Houston, May 2005.
- [9] Snell, R., 1997, 'ISO Offshore Structures Standard', OTC 8421, Houston, Texas, 5-8 May.
- [10] ISO 13819-2 1995, Offshore Structures – Part 2: Fixed Steel Structures. ISO 19902 cancels and replaces ISO 13819
- [11] Wisch, D.J., 1997, 'Fixed Steel Standard: ISO and API Developments – ISO TC 67/SC 7/ WG3', OTC 8423, Houston, Texas, May 1997.
- [12] Guenard.Y., Goyet J. and Labeyrie J., 'Structural Safety Evaluation of Steel Jacket Platforms', The Society of Naval Architects and Marine Engineers, Virginia, oct, 5-6, 1987
- [13] PAFA Consulting Engineers for HSE, 'Implications for the assessment of existing fixed steel structures of proposed ISO 13819-2 member strength formulations', final report, 2000
- [14] Advance Mechanics and Engineering Ltd. For HSE, 'Buckling of offshore structures: assessment of code limitations', Offshore Technology Report-OTO 97-049.
- [15] MSL Engineering Ltd. For HSE, 'Load factor calibration for ISO 13819 Regional Annex: Component resistance', Offshore Technology Report 2000/072
- [16] Hellan,O., Moan,T., and Drange,S.O., 1994, 'Use of Non – linear Pushover Analysis in Ultimate Limit State Design and Integrity Assessment of Jacket Structures', Proceedings of 7th International Conference on the Behaviour of Offshore Structures BOSS 1994.
- [17] Knapp, A.E. and Dixon, D.A., 1972, 'The use of X-bracing in fixed offshore platform', Proc. 5th Offshore technology Conference, OTC Paper no.1663, Houston.
- [18] Potty N.S., Nizamani Z.A. and Idrus A.B., 'Load and resistance factor calibration methodology for offshore jacket platforms in Malaysia', First Makassar International Conference on Civil Engineering (MICCE2010), Indonesia, March 9-10, 2010, ISBN 978-602-95227-0-9.
- [19] Potty N.S., Nizamani Z.A. and Idrus A.B., 'Tubular strength modelling-comparison of API RP2A WSD, API RP2A LRFD and ISO19902', International conference on sustainable building and infrastructure, 15-17 June, 2010 Kuala Lumpur, ISBN 978-983-227-23-9
- [20] Potty N.S., Nizamani Z.A. and Idrus A.B., 'Pile-sleeve strength modelling in API RP2A WSD, API RP2A LRFD and ISO 19902', International conference on sustainable building & infrastructure, 15-17 June, 2010 Kuala Lumpur, ISBN 978-983-227-23-9
- [21] Potty N.S., Nizamani Z.A., Idrus A.B., 'Hydrodynamic load modelling of offshore jacket platform', Asia Pacific offshore conference Kuala Lumpur, 13-14 December, 2010
- [22] Potty N.S., Nizamani Z.A. and Idrus A.B., 'Comparison of foundation strength modelling of jacket platforms in API RP2A codes and ISO 19902', Asia Pacific offshore conference Kuala Lumpur, 13-14 December, 2010
- [23] Potty N.S., Nizamani Z.A. and Idrus A.B., 'Strength of Tubular Members– Numerical Comparison of API RP2A to ISO Codes', Proceedings of the Ninth (2010) ISOPE Pacific/Asia Offshore Mechanics Symposium, Busan, Korea, November 14-17, 2010, The International Society of Offshore and Polar Engineers ISBN 978-1-880653-79-1: ISSN 1946-004X

- [24] Potty N.S., Nizamani Z.A. and Idrus A.B., ‘ Offshore Jacket Platforms-LRFD Code Calibration’, International conference on sustainable building and infrastructure, 15-17 June, 2010 Kuala Lumpur, ISBN 978-983-227-23-9
- [25] Potty N.S, Nizamani Z.A. and Idrus A.B, ‘Sustainable infrastructure through rational codes using reliability and code calibration’, International conference on sustainable building and infrastructure, 15-17 June, 2010 Kuala Lumpur, ISBN 978-983-227-23-9
- [26] Potty N.S., Cossa N.J, Nizamani Z.A. and Idrus A.B, ‘Tubular joint strength models in API RP2A WSD, API RP2A LRFD & ISO 19902’, World Engineering Congress 2010, 2-5, August 2010, Kuching, Sarawak, Malaysia, Conference on Buildings and Infrastructure Technology
- [27] Arazi B. Idrus, Narayanan Sambu Potty, Mohd. Foad Abdul Hamid, Zafarullah Nizamani and Nelson J Cossa, ‘Resistance Parameters Statistics for Jacket Platforms in Offshore Malaysia’, The Twenty-first (2011) International Offshore (Ocean) and Polar Engineering Conference, (ISOPE) Hawaii, USA, June 19–24,2011, (paper accepted for presentation)
- [28] A. B. Idrus, Narayanan S. P., M. F. A. Hamid, N. J. Cossa and Z. Nizamani, “Statistical parameters of steel tubular member design for offshore platforms in Malaysia”, 7th International Conference on Steel and Aluminium Structures 13 – 15 July 2011, Kuching, Sarawak, Malaysia, (paper accepted for presentation)
- [29] A. B. Idrus, Narayanan S. P., M. F. A. Hamid, Z. Nizamani, and N. J. Cossa, ‘Selection of environmental parameters for offshore jacket platform design in Malaysia’, 7th International Conference on Steel and Aluminium Structures 13 – 15 July 2011, Kuching, Sarawak, Malaysia, (paper accepted for presentation)

PROFILES



IR. DR ARAZI BIN IDRUS is an Associate Professor at the Department of Civil Engineering, Universiti Teknologi PETRONAS, Malaysia. He graduated with a B Eng (Hons) degree in Civil and Structural Engineering from Sheffield University, UK in 1984, an M Sc degree from Cranfield University, UK in 1994 and a PhD degree from Imperial College of Science, Technology and Medicine, London, UK in 2001. His fields of interest include Blast Design, LRFD, IBS and Project Management. He is a Fellow of the Institution of Engineers, Malaysia and a registered professional engineer with the Board of Engineers, Malaysia. Prior to joining the academic world, he worked as a civil engineer with the Public Works Department for 17 years



EN. ZAFARULLAH NIZAMANI is a Ph.D. student, in civil engineering department at Universiti Teknologi PETRONAS, Malaysia. His research interest is “Environmental load and steel tubular resistance factors for Jacket platforms in Malaysia”. He has achieved Bachelor in civil engineering from Mehran University of Engineering and Technology, Jamshoro in 1991 and Masters in structural engineering from N.E.D. University of engineering and technology Karachi in 2003.



IR. DR NARAYANAN SAMBU POTTY received his Bachelor of Technology in Civil Engineering from Kerala University and Master of Technology degree from National Institute of Technology in Kerala, India. His PhD work “Improving Cyclone Resistant Characteristics of Roof Cladding of Industrial Sheds” was done at Indian Institute of Technology Madras India. Currently Associate Professor at UTP, he has earlier worked in Nagarjuna Steels Ltd., TKM College of Engineering Kerala and Universiti Malaysia Sabah. His main research areas are steel and concrete structures, offshore structures and construction management.