Comparison of tubular joint strength provisions in codes and standards

Prepared by **Bomel Limited**
for the Health and Safety Executive

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1. INTRODUCTION

The purpose of this technical note is to present a comparison of the technical provisions concerning the static strength of tubular joints given in the following documents:

1. API RP2A WSD and LRFD [1] and [2]
2. HSE 4th Edition Guidance Notes (GNs) [3]
3. Draft ISO standard for fixed steel offshore structures [5] and [6]
4. NORSOK standard for the design of steel offshore structures [8].

Generically, code provisions for the static strength of tubular joints in offshore steel structures cover the following areas:

1. Joint capacity
    - i. axial and moment capacities
    - ii. geometric effects
    - iii. chord stress effects
    - iv. brace load interaction
    - v. validity ranges

2. Relative joint / member strength
3. Joint classification
4. Joint detailing
5. Safety format.

Some general background to the various documents is given in Section 2. Items 1 to 5 are covered in subsections of Section 3. Some overall conclusions are presented in Section 4. References are given in Section 5.

2. GENERAL BACKGROUND

2.1 TUBULAR JOINT CAPACITIES IN THE DESIGN CONTEXT

2.1.1 Code Provisions

Code provisions for the static strength of tubular joints in offshore structures generally cover the following:

1. Joint capacity
    i. configuration (T/Y, X/DT, K; complex grouted, multiplanar etc.)
    ii. loading modes (P, M_{ipb}, M_{opb})
    iii. geometric effects (Q_u)
    iv. chord stress effects (Q_f)
    v. brace load interactions (P-M)
    vi. validity range
2. Relative joint / member strength
3. Joint classification
4. Joint detailing
5. Safety format.

Joint capacity provisions are largely empirical given the complex interaction between shell bending and membrane action which forms the basis of tubular joint strength. For complex joints and joint detailing practices for which test data are sparse, experience and engineering judgement influence the recommendations. Finite element analysis is being used increasingly in complex cases, but the data obtained is limited by the difficulties associated with modelling fracture failure modes. Joint classification and requirements for relative joint and member strengths are based on principles of engineering mechanics.

2.1.2 Basis of Equations

In applying a design code or standard it is important to appreciate the basis of the given equations, particularly the way uncertainty and inherent variability are handled. In the case of tubular joints:

- Many tests are undertaken for the simplest joints and loading modes in different laboratories to determine capacity.

- The results are assembled (usually by a third party) and screened to ensure as far as possible that results are comparable and applicable to offshore tubular joints.

- Best-fit formulae are derived based on measured material and geometric properties, relating capacity to non-dimensional parameters. However, the data exhibit significant scatter about the mean due, for example, to differences in component testing methods, as well as to inherent variability that may be exhibited within jacket structures.

- Design formulae are developed to provide sufficient confidence that the actual strength will be greater than the nominal value assumed in design. In some cases, this may be based on a lower bound fit to the data or on a characteristic evaluation (i.e. mean minus N standard deviations - where N depends on the number of results available and the degree of confidence required, say, 95% survivability with 50% confidence).

- The formulae to account for simple joint capacity are combined with allowances for chord stress effects, the combined action of different loading modes, etc., to give all-encompassing equations for joint strength. Few data exist for a realistic combination of loads and geometries against which to compare the resulting calculated capacities.

The empirical expressions for axial capacity, P, and moment capacities, M, of tubular joints are generally consistent across all codes taking the form:

$$P = K \frac{F_y T^2}{\sin\theta} Q_u Q_f$$

$$M = K \frac{F_y T^2}{\sin\theta} d Q_u Q_f$$

where

F_y = chord yield stress
T = chord wall thickness
θ = included angle between brace and chord
d = brace diameter
Q_u = geometric modifier, f (β, γ, ζ, etc.)
Q_f = chord stress modifier
β = brace diameter (d) / chord diameter (D) ratio
γ = chord slenderness (D/2T)
ζ = K joint gap (g) to chord diameter ratio (g/D)
K = constant / multiplier.

The specific formulations for Q_u and Q_f differ as do the forms for axial and moment interaction.

2.1.3 Design Process

The resistance formulae are put into a code checking equation to determine if the load demand is less than the available capacity with an appropriate margin of safety. Working stress design (WSD) or limit state (alternatively formulated as load and resistance factors design (LRFD)) approaches may be used. In traditional WSD practice the check is that:

$$\frac{\text{nominal\_strength}}{\text{safety\_factor}} \geq \sum \text{nominal\_loads}$$

Whereas for LRFD partial factors reflect the different degree of uncertainty in the various elements of loading and resistance giving:

$$\text{resistance\_factor} \times \text{nominal\_strength} \geq \sum \text{load\_factor} \times \text{nominal\_load}$$

Resistance factors are generally less than one and account for the potential variability in capacity due to inherent uncertainty in the material (thickness) and fabrication tolerance in the structure.

Limit state approaches provide the mechanism to design to a target reliability with partial factors selected accordingly. However the evaluation of codes is made to move from WSD to LRFD practices, calibrating partial factors to deliver safety levels on average equivalent to earlier WSD designs.

In the design check process, component forces or stresses are determined by linear elastic analysis methods and entered into programmed post-processors effecting the code equations. In certain respects, the analytical assumptions differ from those underlying the equations. For example, an axially loaded T joint in the laboratory generates bending stresses in the chord but their effect is generally neglected in formulating capacity equations. Extreme fibre stresses calculated in the chord of a T joint in a jacket, however, combine the equilibrium stress with additional load effects. The total is then used to assess chord stress effects. It is convenient to extract total stresses in this way but it is impractical to re-evaluate the test data; the degree of end fixity in the test (pinned vs fixed) is generally unknown and to extract their influence would require a priori quantification of the effect on capacity.

The complexities of real jacket nodes are generally simplified to render them amenable to assessment against the empirical equations. Individual planes are extracted and assessed independently from out-of-plane influences.

The assessment is subject also to a classification of the joint action within the plane. A combined evaluation based on geometry and a conservative hierarchy of load effects is generally applied. The degree of tolerance on the classification (e.g. K joint load balanced to within ±5%, 10% etc.) varies with software package and user.

The above is by no means an exhaustive list of the steps but it serves to highlight the implicit assumptions and approximations in assessing the design requirements for tubular joints. It also presents the framework against which many of the subsequent observations in this technical note can be interpreted.

2.2 API RP2A

The reference editions for RP2A in this study are WSD 20th Edition [1] and LRFD 1st Edition [2] both published in 1993. The tubular joint provisions are identical in respect of basic nominal capacities between WSD and LRFD and date from the 15th Edition of WSD published in 1984. Their introduction represented a step change in API practice. Earlier editions from the 1970s were generally based on an underestimate of capacity and had been presented in a punching shear format, which does not represent the failure mode for many tubular joints. Although improvements had been introduced as knowledge of different joint characteristics emerged, the 15th Edition brought a major overhaul of the provisions. The capacity equations are presented as a lower bound representation of the available data. In the transition from WSD to LRFD the opportunity was taken to revise the interaction formula to avoid numerical solution problems for highly utilised joints. The commentary to LRFD [2] presents detailed discussion of the calibration process. In summary, reasonably uniform and consistent reliabilities between the WSD and LRFD versions were obtained with resistance factors of 0.95 generally and 0.9 in the specific case of tension loaded T/Y and X joints. The distinction reflects the additional uncertainty associated with crack initiation on which the tension equations are based rather than ultimate strength.

The API-LRFD calibration exercise also included a direct comparison of resulting interaction ratios (IRs) for specific combinations of load and resistance factors as opposed to blanket WSD safety factors. The LRFD : WSD ratio of IRs generally fell in the ±20% range but the comparison with IRs from earlier editions showed much greater variation (±60% in the extreme).

2.3 HSE 4TH EDITION GUIDANCE NOTES

Although the 15th Edition of RP2A represented a step change in API practice, subsequent work identified a significant body of additional test data. This was included in expanded databases which formed the basis of static strength equations in the HSE 4th Edition Guidance Notes (1990) [3]. The additional data enabled different load and geometry effects to be distinguished giving a more 'refined' set of equations. In addition the derivation of design equations was based on a lower characteristic formulation rather than the lower bound approach in RP2A. However the overall approach for code checking was based on working stress, with characteristic capacities being reduced by a safety factor to give allowable loads.

Although the Guidance Notes were withdrawn in 1998 (for regulatory reasons rather than any specific concern over technical rigour of the tubular joint provisions), the background to the static strength guidance is openly available [4].

In BOMEL's Tubular Joints Group project, the HSE database was further expanded and re-screened and the goodness of fit of existing design equations assessed. Focusing on the basic Q_u geometric influence for different loading modes and joint types, the HSE equations represented the underlying data most consistently compared with RP2A [1] and other Canadian, Norwegian and European practices. Although individual equations provided a better fit to the data in certain cases a 'mix and match' selection is inappropriate. The HSE equations continue to represent the best available set of equations for assessing tubular joint capacity, until the proposed ISO equations [6] are accepted and adopted.

A further advantage is that the background document [4] provides the mean equations, as well as design characteristic values. The former are particularly required for the assessment of existing structures, where joints may fail to satisfy design criteria and the 'actual' capacity needs to be considered.

2.4 ISO 13819-2

The first edition of ISO 13819 [5] adopts the provisions of RP2A-LRFD [2]. The starting point for the technical core group preparing the second edition was to carry the existing recommendations forward without change unless they were shown to be inadequate. A number of factors influenced the approach. The lower bound formulation in RP2A (see Subsection 2.2) is not consistent with the more rigorous statistical approach generally adopted for limit state codes. Work by the TJ Group as well as others had shown that the RP2A formulae did not present the best representation of newly available data (see Subsection 2.3). As a result more recent better formulae had been produced (e.g. HSE Guidance Notes). Furthermore the MSL JIP [7] had further expanded and re-screened the data and instigated supplementary finite element (FE) analyses on the basis of which yet another set of capacity formulae had been derived.

The ISO technical core group therefore took these equations as the basis for the second edition of ISO 13819-2 and worked these in conjunction with other design considerations for achieving adequate static strength of tubular joints.

Development of the proposed text has been an iterative process with a number of internal drafts within the core group, some of which have formed part of consolidated drafts of the whole standard circulated for industry comment.

The code comparison in Section 3 presents the most recent equations (included in the formal 'Committee Draft' of May 1999). The draft text presents design formulae and within the commentary mean bias and coefficient of variation (COV) statistics are presented enabling the formulae to be used for assessment purposes. It is understood that the chord stress parameter, Q_f, is among a number of areas still under scrutiny by the ISO Technical Core Group.

2.4 NORSOK

The NORSOK standard has, to a very large extent, adopted the provisions of contemporaneous drafts of the ISO standard. This would appear to be Draft C [6], and would therefore lead to some differences between NORSOK and the current draft ISO, which are pointed out in the detailed comparisons in Section 3, below.

3. COMPARISONS OF TECHNICAL PROVISIONS

3.1 PREAMBLE

This section compares the principal provisions of the API [2], withdrawn HSE [3], draft ISO [6] and NORSOK [8] codes. Shorthand reference to 'API', 'HSE', 'ISO' and ‘NORSOK’ will be made for convenience. In addition to quantified recommendations, the reference documents provide other general guidance, but it is not practicable for every aspect to be covered here. To apply the codes, the reader must refer to the original documents. The comparison covers the aspects of tubular joint strength listed in Subsection 2.1.1.

3.2 JOINT CAPACITY

3.2.1 Axial and Moment Capacities

All four codes adopt the basic axial and moment capacity formulations as given in Subsection 2.1.2. However, the expressions for Q_u and Q_f differ as shown below. The constant K in the moment equation is unity in HSE, ISO and NORSOK, but 0.8 in API. For the purpose of comparison the 0.8 factor is therefore combined with the API Q_u values. Similarly for axial loading HSE includes a multiplier K_a (a function of brace inclination) and again this is presented with Q_u.

3.2.2 Geometric Effects

Geometric effects are embodied in the Q_u factor. Table 3.1 compares the Q_u formulae presented in the four codes for each joint geometry (T/Y, DT/X, K) and loading mode (axial tension, axial compression, in-plane bending, out-of-plane bending). For the most part the expressions used by NORSOK follow those in the latest ISO, the only exception is for DT/X joints in compression, for which NORSOK follows the provisions set out in ISO Draft C.

In all cases the expressions are reached as an empirical fit to the available data (a lower bound in API and statistically determined characteristics in HSE, ISO and NORSOK). Each set was derived on the basis of independent datasets and the constants differ as a result. In terms of the fundamental relationships expressed in the equations the following observations with respect to Table 3.1 can be made:

- **T/Y joints in compression**. ISO and NORSOK, as HSE, identify a strength enhancement for high β joints. At low β ISO/NORSOK indicate less capacity than either API or HSE. At high β the ISO/NORSOK capacity is between API and HSE values.

- **T/Y joints in tension**. ISO, NORSOK and API equations are based on a 'first crack' limit whereas the HSE formula relates to ultimate strength; HSE therefore indicates significantly higher capacities. ISO/NORSOK capacities are generally greater than API (for $\beta > 0.3$). At $\beta = 1.0$ the ISO/NORSOK first crack design capacity is equivalent to the ultimate strength value given in HSE.

- **DT/X joints in compression**. The ISO formula is modified from Draft C to introduce a γ influence neglected in NORSOK, API and HSE. For $\gamma \approx 20$ the DT joint design capacities from API, HSE, ISO and NORSOK are almost identical across a range of β. The latest ISO equations give a reduced enhancement with increasing β for low γ but for high γ joints the effect is stronger.

- **DT/X joints in tension.** As for T/Y joints in tension, ISO and NORSOK, as API, relate to first crack whereas HSE is based on ultimate strength therefore giving the greatest capacities. Where HSE indicated a gradual enhancement in capacity for high β by including a Q_β factor, in ISO/NORSOK the influence is limited to β in the range 0.9 to 1.0 where the membrane influence becomes strongest. As for DT/X joints in compression ISO and NORSOK introduce a γ influence; with high γ / high β joints having greater capacity. As for T/Y joints in tension, ISO first crack capacities at $\beta = 1.0$ are comparable (depending on γ) to the ultimate values given by HSE. For $\beta < 0.9$ the ISO/NORSOK capacity is somewhat lower than API.

- **K joints axial**. ISO and NORSOK, as HSE, give a relative increase in strength for high β joints (via $Q_\beta^{0.5}$) not seen in API. At low β the ISO/NORSOK capacity is in some instances less than API depending on the gap between K joint weld toes. The gap influence is complex and is expressed differently in all four codes. Both ISO, NORSOK and HSE equations can be expressed in terms of the g/D ratio although the applicability for ISO/NORSOK is based on g/T. The power of the ISO/NORSOK approach is that it provides continuity between gap and overlap configurations. In API and HSE a separate formulation addressing shear at the common weld of overlapping joints is invoked.

- **All joints IPB**. ISO and NORSOK, as HSE, includes a γ influence on IPB capacity ($\gamma^{0.5}$) which is not included in API. Evidence for the $\sin\theta$ influence in HSE was not found for the ISO/NORSOK equations. In general the ISO/NORSOK IPB capacities are greater than in API.

- **All joints OPB**. Where API and HSE include a β or Q_β influence on OPB capacity of a similar form, the relationship in ISO/NORSOK is quite different.

Capacity relates to the γ ratio but the strength of influence varies with β (expressed as a β^2 power). Where HSE distinguished between X and Y / T / K joints, ISO/NORSOK and API, present a single equation for all joint types. Despite the change in the formulation the capacities are reasonably similar between the four codes for moderate γ.

3.2.3 Chord Stress Effects

The chord effects are embodied in the Q_f factor. Table 3.2 compares the Q_f formulae presented in the four codes.

The HSE and API formulations are identical on account of the limited data available to both background studies. The HSE formula is however presented in terms of forces and moments as opposed to stresses. The ISO provisions are different in a number of respects:

- The chord stress effects are independent from γ.

- The interaction is based on the comparison between factored loads and section capacities rather than stresses and yield.

- The significance of chord forces and moments varies with joint type and loading mode in an attempt to separate the influence of equilibrium effects due to brace loading already accounted for in Q_u.

- In addition to a detrimental effect of chord compression, the Q_f factor also applies for DT/X joints with $\beta > 0.9$ if chord axial tension stress is less than the combined stress due to moments.

The changes result in a significant increase in calculated capacity for high γ joint with net compressive stresses in the chord.

NORSOK uses expressions from Draft C of ISO. Key aspects of the NORSOK formulation used are that:

- The interaction is based on factored applied stresses on the action side, and yield strength and characteristic chord bending strength on the resistance side. Thus, no partial safety factors are applied to the resistance components.

- In addition to a detrimental effect of chord compression, the Q_f factor also applies for DT/X joints with $\beta > 0.9$ if chord axial tension stress is less than the combined stress due to moments.

3.2.4 Brace Load Interaction

Table 3.3 compares the interaction formulae in all four codes. It can be seen that the hyperbolic expressions have not been retained in ISO from API, and the ISO formulation is identical to HSE. The NORSOK formula, whilst different in appearance from that of ISO, is identical in format. This format is more amenable to assessment of joints in existing structures where utilisation may be beyond current design capacities for which the API expressions may be insoluble.

The expressions are similar, as they are intended to be, at and around full utilisation of the joint. However for lower levels of load, very significant differences result on account of the different representation of non-linear interactions at failure. Utilisation comparisons away from unity should therefore by viewed with caution.

3.2.5 Validity Ranges

Table 3.4 compares the validity ranges stated within the codes. Although limitations are not presented by API, the ISO, NORSOK and HSE conditions are very similar. The significant expansion in the ISO and NORSOK codes is on yield stress extending the validity from 400 to 500 N/mm^2, together with a relaxation in the restriction on yield to ultimate strength ratio (F_y:F_u). Where the yield strength of the chord was to be taken as the minimum of the nominal yield or 0.7 times the ultimate stress, F_u (0.66 in API), the ISO/NORSOK limit is 0.8 F_u, which is above the level of practical significance for most structural steels in current offshore use for fixed structures.

Code	g	b	q	**F_y (N/mm^2)**
API*	10 - 50	0.2 - 1.0	30 - 90	333 - 500
HSE	9 - 50	0.15 - 1.0	30 - 90	≤ 400
ISO	10 - 50	0.2 - 1.0	30 - 90	≤ 500
NORSOK	10 - 50	0.2 - 1.0	30 - 90	≤ 500
* not specified in code but deduced from background in [9] i.e. ranges in databases stated above.				

Table 3.4 Validity Ranges in Codes

3.3 RELATIVE JOINT / MEMBER STRENGTH

The principal requirement is for joints to be sized to withstand the design loads.

The additional provisions regarding the relative strength of joints compared to the incoming members is different in ISO compared with API. No specific requirements were set down in the HSE Guidance Notes which did not give explicit treatment of member design. In ISO the requirement for primary or 'significant' joints is:

$$\mathrm{IR}_{\mathrm{joint}} \leq 85\% \ \mathrm{IR}_{\mathrm{brace}}$$

whereas in API the provision is expressed as

$$\text{joint capacity} \geq 50\% \text{ brace capacity}$$

or alternatively

$$\frac{F_{yb}}{F_{yc}} \frac{(\gamma \tau \sin\theta)}{\left(11 + \frac{1.5}{\beta}\right)} \leq 1$$

in which F_{yb}, F_{yc} are the brace and chord yield stresses and τ is the brace to chord wall thickness ratio.

ISO provisions are an attempt to ensure that joints are stronger than the adjoining braces to give adequate ductility in extreme conditions. It could be argued that this is not an appropriate strategy for assuring ductility, but accepting the premise the basis of utilisation is more rational than inherent capacity. It is assumed that the 15% margin accounts for the greater variability in tubular joint strength and hence different mean bias and partial resistance factors for joint and member equations. In light of the use of modern analysis and automated code checking computer software there are difficulties associated with fulfilling this 15% criterion, however. A comparison of IRs for brace and joint would only be possible after the code checking has been completed; an impractical iteration process would be necessary in the event that the 15% margin was not achieved.

The ISO focus on primary joints means that for many secondary joints, previously governed by minimum capacity requirements, the change represents a relaxation. However for some primary joints the effects may be significantly more onerous. The ISO commentary suggests the net impact should be negligible. The effect may be greatest in regions where fatigue considerations do not play a part in the sizing of joints.

3.4 JOINT CLASSIFICATION

The principles in all four codes are similar in that classification should be based on a combination of geometry and axial load paths within each plane on a conservative basis. ISO and NORSOK suggests the tolerance on 'balanced' loads can be ±10%.

The diagrams used to aid classification of joints are identical in NORSOK and ISO. In comparing these with the equivalent diagram in API, it is found that API covers the same examples, with one exception. ISO/NORSOK includes a DT/Y joint in which 50% of the diagonal force is balanced with a force in the vertical on the same side of the chord in a K-joint, and 50% is balanced with a force in the vertical on the opposite side of the chord in a X-joint. The diagram given in HSE differs from the rest entirely, concentrating on simple Y and X-joints, and the treatment of various K-joints depending on the degree to which the brace loads balance. Other configurations where brace members occur on opposite sides of the chord are dealt with by textual provisions.

3.5 JOINT DETAILING

HSE gives general considerations for joint detailing whereas API and ISO give identical quantified recommendations on the minimum extent of chord can beyond the outermost intersection (D/4 or 300mm) and brace stub lengths (d or 600mm).

API, ISO and NORSOK also provide equations to quantify the partial effectiveness of a short chord can. For K joints, loads are generally transferred in the gap region whereas the influence of the can in resisting overall bending and preventing ovalisation is more significant for Y and X joints.

In API the requirements (which apply only to X joints) take the form:

$$P_{uj} = P_1 + \tfrac{L}{2.5D}[P_2 - P_1] \quad \text{for } L < 2.5D$$

where P_1 is the joint capacity based on the chord member thickness, T
P_2 is the joint capacity based on the chord can thickness, T_c
and L is the can length based on the shortest distance between the brace and can transition.

In ISO the expression applies both to X and Y joints and has been developed further to be:

$$P_{uj} = [r - (1 - r)(\tfrac{T}{T_c})^2]\, P_2$$

where $r = \tfrac{L}{2.5D}$ for $\beta \le 0.9$
and $r = (4\beta - 3)\tfrac{L}{1.5D}$ for $\beta > 0.9$
where $r \le 1$.

As joint capacity is proportional to T^2 the ISO equation reduces to the API expression for Y joints and tension X joints for $\beta < 0.9$. However for compression X joints and all high β X and Y configurations advantage is taken of the can thickness in the γ contribution to Q_u (see Table 3.1). It is not clear whether this is intentional.

For high β joints the alternative formulation for r means that, because of the predominance of local membrane action, even short cans contribute to enhanced capacity.

In NORSOK the formula for P_{uj} is the same as that for ISO. The computation of r is different, however, as follows:

$$r = \tfrac{L}{D} \text{ for } \beta \le 0.9$$
$$r = \beta + (1-\beta)(10\tfrac{L}{D} - 9) \text{ for } \beta > 0.9 .$$

where $r \le 1$.

It must be assumed that ISO Technical Core Group rejected this when introducing an improved formulation in Drafts subsequent to C.

3.6 SAFETY FORMAT

As described in Section 2 the safety format of the WSD (HSE and API WSD) and LRFD (NORSOK, ISO and API LRFD) codes is different.

For both working stress approaches (HSE and API WSD) the allowable joint capacities compared with unfactored loads have all-encompassing safety factors of 1.7 for operating conditions and 1.28 for extreme environmental events comprising live (L), dead (D), environmental (W) load components.

$$\frac{\text{nominal\_strength}}{1.7(\text{or}\,1.28)} \ge \sum L, D, W, \text{etc.}$$

In API LRFD and ISO, the format is:

$$\phi_j \times \text{nominal\_strength} \ge \sum \gamma_L L + \gamma_D D + \gamma_W W$$

where, for API LRFD:

ϕ_j = 0.95 for all joints and loading modes except T/Y and DT/X joints in tension for which j = 0.9

and γ_L and γ_D equal 1.1, or 0.9 and 0.8 if lower loads are more onerous

γ_W = 1.35 but may vary with region, etc.

In ISO it is proposed that a uniform ϕ_j of 0.95 be adopted across all joints. Although the load factors remain to be confirmed, the CD of May 1999 [6] indicates that:

γ_L and γ_D equal 0.9, 1.1 and 1.5, depending on which actions predominate
γ_W = 1.35 but may vary with region, etc.

In NORSOK, the design values are obtained by dividing the characteristic values from the generalised formulae for axial and moment resistance by a material partial safety factor γ_M. This takes a fixed value of 1.15 in all cases (which represents a ϕ value of 0.87). In general terms the safety format appears as:

$$\frac{\text{characteristic\_strength}}{\gamma_M} \geq \sum \gamma_f S_k$$

where S_k are the characteristic values of action effects, and γ_f are the partial safety factors on actions. The latter are to follow the ISO recommendations. Thus NORSOK design strengths can potentially be 1/(1.15 x 0.95) = 0.92 times those of ISO.

The tubular joint checks are in fact expressed not in the linear form as indicated here but in the more complex P-M interaction given in Table 3.3, although the above is illustrative. It should also be noted that the safety format also affects elements within the nominal strength calculation, for example the chord stress effect given in Table 3.2

Code	T/Y Compression	T/Y Tension	DT/X Compression	DT/X Tension	K/YT Balanced axial	IPB	OPB
API-WSD & LRFD	$3.4 + 19\beta$		$(3.4 + 13\beta)Q_\beta$	$3.4 + 19\beta$	$(3.4 + 19\beta)Q_g$	$0.8(3.4 + 19\beta)$ Note a	$0.8\,(3.4 + 7\beta)Q_\beta$ Note a
HSE	$(2\ 20\beta +)Q_\beta^{0.5} K_a$ Note b	$(8 + 22\beta)\,K_a$ Note b	$(2.5 + 14\beta)Q_\beta K_a$ Note b	$(7 + 17\beta)Q_\beta\, K_a$ Note b	$(2 + 20\beta)Q_\beta^{0.5}\, Q_g K_a$ Note b	$5\beta\, \gamma^{0.5}\sin\theta$	$(1.6 + 7\beta)\, Q_\beta$ (Y/K) $(1.6 + 7\beta)\, Q_\beta^{0.5}$ (X)
ISO & NORSOK	$(1.9 + 19\beta)Q_\beta^{0.5}$	30β	$(2.8+X\beta)Q_\beta$ Note c	23β for $\beta \le 0.9$ else $21+(\beta-0.9)(17\gamma-220)$	$(1.9+19\beta)Q_\beta^{0.5}\, Q_g$ Note d	$4.5\beta\, \gamma^{0.5}$	$3.2\gamma^{(0.5\beta^2)}$

where $\beta = d/D,\ \ \gamma = D/2T,\ \ \zeta = g/D,$ $\quad Q_\beta = \dfrac{0.3}{\beta(1-0.833\beta)}$ $\quad K_a = 0.5\left(1+\dfrac{1}{\sin\theta}\right)$

and Q_g for the respective codes is given by:

API $\quad 1.8 - 0.1\dfrac{g}{T}$ for $\gamma \le 20$ or $1.8 - 4\dfrac{g}{D}$ for $\gamma > 20$ $Q_g \ge 1.0$

HSE $\quad 1.7 - 0.9\left(\dfrac{g}{D}\right)^{0.5}$ $\quad Q_g \ge 1.0$

ISO & NORSOK $\quad 1.9 - 0.7\gamma^{0.5}\left(\dfrac{g}{T}\right)^{0.5}$ for $\dfrac{g}{T} \ge 2.0$ or $0.13 + 0.65\,\phi\gamma^{0.5}$ for $\dfrac{g}{T} \le -2.0$

with interpolation between for $-2.0 \le \dfrac{g}{T} \le 2.0$

$\phi = \dfrac{t\,F_{yb}}{T\,F_y}$ in which t and F_{yb} are the brace thickness and yield stress and T and F_y relate to the chord

a In API 0.8 is presented as a multiplier on moment capacity rather than an element of Q_u

b In HSE K_a is presented as a multiplier on axial capacity rather than an element of Q_u

c In ISO draft C & NORSOK expression for DT/X joints is X =14 (ie. independent of γ); latest ISO X = $(12+0.1\gamma)$ (ie. dependent on γ)

d In ISO draft C & NORSOK an additional angle capacity factor Q_w was included for joints where Q_{yy} = 1.0, when $\theta_1 \le 4\theta_c - 90°$ or $(110° + 4\theta_c - \theta_1)/200°$ otherwise

Table 3.1 Comparison of Q_u Factors

Code	Formulation
API LRFD	1 if all chord stresses are tensile, or $1 - \lambda \gamma A^2 \quad A = \frac{(f_{ax}^2 + f_{ipb}^2 + f_{opb}^2)^{0.5}}{\phi_q F_y}$ $\lambda_{braceax} = 0.030$ $\lambda_{braceipb} = 0.045$ $\lambda_{braceopb} = 0.021$ f_{ax}, f_{ipb}, f_{opb}, = factored chord stress components
API WSD	1 if all chord stresses are tensile, or $1 - \lambda \gamma A^2 \quad A = \frac{(f_{ax}^2 + f_{ipb}^2 + f_{opb}^2)^{0.5}}{0.6\ F_y}$ $\lambda_{braceax} = 0.030$ $\lambda_{braceipb} = 0.045$ $\lambda_{braceopb} = 0.021$ plus ⅓ storm increase on denominator f_{ax}, f_{ipb}, f_{opb}, = unfactored chord stress components
HSE	1 if all chord stresses are tensile, $P_{tension} \geq \frac{1}{0.23D}(M_i^2 + M_o^2)^{0.5}$, or $\lambda_{braceax} = 0.030$ $1 - 2.890 \lambda \gamma A^2 \quad A = \frac{((0.23PD)^2 + M_i^2 + M_o^2)^{0.5}}{0.72\ D^2\ T\ F_y}$ $\lambda_{braceipb} = 0.045$ $\lambda_{braceopb} = 0.021$ plus ⅓ storm increase on denominator P, M are unfactored chord forces
ISO	1 if all chord stresses are tensile (except for DT/X joints with $\beta > 0.9$) $\lambda_{braceax} = 0.030$ $1 - \lambda A^2 \quad A = \frac{\left(C_1 \left(\frac{P_D}{P_y}\right)^2 + C_2 \left(\frac{M_D}{M_P}\right)_{IPB}^2 + C_2 \left(\frac{M_D}{M_P}\right)_{OPB}^2\right)^{0.5}}{\phi_q}$ $\lambda_{braceipb} = 0.045$ $\lambda_{braceopb} = 0.021$ P_D, M_D are factored chord loads ϕ_q is material resistance factor C_1 C_2 T/Y joints under brace axial load 25 11 K joints under balanced axial load 14 43 T/Y and K joints under brace moment, DT/X joints under any brace load 25 43
NORSOK	1 if all chord stresses are tensile (except for DT/X joints with $\beta > 0.9$) $\lambda_{braceax} = 0.030$ $1 - \lambda . c . A^2 \quad A^2 = \left(\frac{\sigma_{a,Sd}}{f_y}\right)^{.2} + \left(\frac{\sigma_{my,Sd}^2 + \sigma_{mz,Sd}^2}{f_m^2}\right)$ $\lambda_{braceipb} = 0.045$ $\lambda_{braceopb} = 0.021$ $\sigma_{...,Sd}$ = design axial and bending stresses f_y = yield strength, f_m = chord characteristic bending strength c = 14 for Y and K joints and 25 for X joints (i.e. ISO Draft C)

Table 3.2 Comparison of Q_f Factors

Code	Interaction criterion
API LRFD	$1-\cos\left[\frac{\pi}{2}\left(\frac{P_D}{\phi_j P_{uj}}\right)\right]+\left[\left(\frac{M_D}{\phi_j M_{uj}}\right)_{IPB}^2+\left(\frac{M_D}{\phi_j M_{uj}}\right)_{OPB}^2\right]^{0.5}$
API WSD	$\left\lvert\frac{P}{P_a}\right\rvert+\frac{2}{\pi}\arcsin\left[\left(\frac{M}{M_a}\right)_{IPB}^2+\left(\frac{M}{M_a}\right)_{OPB}^2\right]^{0.5}$ $\left(\frac{M}{M_a}\right)_{IPB}^2+\left(\frac{M}{M_a}\right)_{OPB}^2$
HSE	$\left\lvert\frac{P}{P_a}\right\rvert+\left(\frac{M}{M_a}\right)_{IPB}^2+\left\lvert\frac{M}{M_a}\right\rvert_{OPB}$
ISO	$\left\lvert\frac{P_D}{\phi_j P_u}\right\rvert+\left(\frac{M_D}{\phi_j M_u}\right)_{IPB}^2+\left\lvert\frac{M_D}{\phi_j M_u}\right\rvert_{OPB}$
NORSOK	$\frac{N_{Sd}}{N_{Rd}}+\left[\frac{M_{y,Sd}}{M_{y,Rd}}\right]^2+\frac{M_{z,Sd}}{M_{z,Rd}}$

where in working stress practice:
P, M are the unfactored brace loads
P_a, M_a are the allowable forces and moments including safety factors
and in limit state formulations:
P_D and M_D are the factored brace loads
P_u, M_u are the characteristic capacities
ϕ_j are the joint resistance factors
N_{Sd}, $M_{y,Sd}$, $M_{z,Sd}$ are the design brace loads (factored), y = in-plane, z = out-of-plane
N_{Rd}, $M_{y,Rd}$, $M_{z,Rd}$ are the design resistances (factored)

Table 3.3 Comparison of P-M Interaction Curves

4. CONCLUSIONS

1. In this technical note comparisons have been made between the following documents:

   - API RP2A WSD and LRFD [1] and [2]
   - HSE 4th edition Guidance Notes [3]
   - Draft ISO standard for fixed steel offshore structures [6]
   - NORSOK standard for the design of steel offshore structures [8].

2. All four use the same basic formulae for computing the characteristic strengths in respect of axial and moment resistances. Differences do occur in the Q_u (geometric) and Q_f (chord effects) factors, leading to differences in the characteristic strengths calculated.

3. The NORSOK standard tends to follow the ISO document, but the older draft C version, so that differences between the two relate to the revisions made to ISO, hence in NORSOK:

   - Q_u - the expression for DT/X joints is taken to be independent of γ
   - Q_f - the expression uses design axial and bending stresses in the actions components, along with characteristic yield strength and chord bending strength in the resistance components, i.e. without the partial safety factors on resistance.

4. The interaction criterion (P - M) for NORSOK takes the same format as that for ISO and HSE, which in turn is different from those used for both API codes. Where the formula used is similar, differences occur because of the differences between the safety formats of the codes (i.e. working stress versus limit state/LRFD formats):

	In Axial Load - Bending Interaction Equation:	
Code	Applied loads factored?	Resistances factored?
API WSD	No	Yes
HSE	No	Yes
API LRFD	Yes	Yes
ISO	Yes	Yes
NORSOK	Yes	Yes

5. In terms of safety formats, API WSD and HSE are working stress (“partial” safety factor on resistances only), whereas API LRFD, ISO and NORSOK are limit state/LRFD (partial safety factors on load and resistance).

	“Partial Safety” Factors on:	
Code	Actions/Loads	Resistances/Strengths
API WSD	N/A	Divisors: 1.7 or 1.28 depending on design condition
HSE	N/A	
API LRFD	Multipliers: 0.8, 0.9, 1.1 & 1.35, depending on load type and design condition	Multiplier: 0.95
ISO	Multipliers: 0.9, 1.1, 1.35 & 1.5 depending on action type and design condition	Multiplier: 0.95
NORSOK		Divisor: 1.15

5. REFERENCES

1. American Petroleum Institute. 'Recommended practice for planning, designing and constructing fixed offshore platforms - working stress design', API RP2A-WSD, 20th edition, July 1993.

2. American Petroleum Institute. 'Recommended practice for planning, designing and constructing fixed offshore platforms - load and resistance factor design', API RP2A-LRFD, 1st edition, July 1993.

3. Health and Safety Executive. 'Offshore installations, guidance on design, construction and certification', 1990 plus amendments [withdrawn 1998].

4. Department of Energy. 'Background to the new static strength guidance for tubular joints in steel offshore structures', Offshore Technology Report, OTH 89 308, HMSO, 1990.

5. International Standards Organisation. 'Petroleum and Natural Gas Industries - Offshore Structures - Part 2: Fixed Steel Structures', First Edition, 1995.

6. International Standards Organisation. 'Petroleum and Natural Gas Industries - Offshore Structures - Part 2: Fixed Steel Structures', Second Edition Draft B, November 1996; Draft C, July 1997; Committee Draft (CD), May 1999.

7. Dier, A F and Lalani, M. 'New code formulations for tubular joint strength', International Symposium on Tubular Structures, 1997.

8. NORSOK Standard. ‘Design of Steel Structures’. N-004. Rev 1, December 1998.

9. Yura, J A, Zettlemoyer, N and Edwards, I F. 'Ultimate capacity equations for tubular joints', OTC Paper 3690, Offshore Technology Conference, Houston, May 1980.

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