TORSION INTERACTION IN TUBULARS IN OFFSHORE STRUCTURES AND JACK-UPS

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ABSTRACT

Torsion is not traditionally dealt with in standards applicable to offshore structures because of the relatively low level of torsion experienced by such structures. However, for some years, ISO 19902 has been used for the design of wind turbine support structures which can experience high torsional loading. Torsional effects can also become important considerations in the event of damage to tubulars or during 'rack-phase difference' incidents in jack-ups. The tubular member strength formulae in the 2020 Edition of ISO 19902 were extended to include torsional effects which have since been adopted in ISO 19905-1.

An examination of other standards that could be used for the design of circular tubulars reveals a variety of approaches in dealing with torsional effects. The standards in question are EN 1993-1-1, AISC 360 and Norsok N-004. Comparisons are made between these various formulations, those of ISO 19902 and those generated by assuming the Mises yield condition provides an appropriate basis for correctly assessing strength under these combined loading conditions. The considered formulations involve interaction between beam and torsional shears, beam shear and bending, torsion and bending, beam shear, torsion and bending, and beam shear, torsion and axial force. Only stocky cross-sections are considered so behaviour is limited to the plastic range.

Significant differences are found between some of the design approaches with few matching the Mises interaction curves. Conservative and non-conservative estimates are found in all standards. These are highlighted and recommendations made for improving them.

KEY WORDS: Tubulars, torsion, jack-ups, fixed steel offshore structures, interaction formulae.

INTRODUCTION

Beam shear and torsion are normally treated as second-order effects in structural steel design, particularly in circular tubulars because of their high torsional stiffness and more so in compact sections when fully plastic conditions prevail. This has led to these shear effects being ignored when relatively low in value, e.g., in BS 5950-1 [1], beam shear less than 60% of shear strength is ignored when considering bending strength, AISC 360 [2] ignores torsion when less than 20% of available torsional strength, Norsok N-004 [3] bending strength is not affected by shear less than 40% of shear strength, and EN 1993-1-1 [4] bending strength ignores shear and torsion when less than 50% of shear strength.

However, the offshore wind turbine industry brought torsion into focus as many of its support structures are constructed of circular tubulars and its loading regimes can impose torsional effects on such structures. Use had been made of ISO 19902 for the design of such structures but guidance on design for torsional effects in its first edition was limited. Because of this dearth of relevant design guidance and in anticipation of the need for ISO/TC 67/SC 7 *Offshore Structures* to transition to lower carbon/renewable energy production, the tubular member strength formulae in ISO 19902:2020 Clause 13 *Strength of tubular members* were extended to include torsion. These same formulae have been adopted in the latest version of ISO 19905-1 although written in force terms rather than the stress terms as in ISO 19902. Torsion is not normally of concern when sizing tubular members in fixed steel structures or jack-ups. However, in the event of damage to tubulars or during 'rack-phase difference' incidents, torsional effects can become important considerations.

Inherent in the treatment of torsion in tubulars is that only St Venant's shear is of relevance and that the warping normally associated with open structural sections can be ignored. An initial consideration is that torsional shear and beam shear are independent so that on one 'web' of a tubular, these shears oppose each other while on the other 'web', they add: this simple addition was adopted in ISO 19902 for considering interaction between shear and torsion, consistent with both ANSI-AISC 360-16 and EN 1993-1-1 requirements. ISO 19902 also adopted the AISC 360 assumption to ignore torsion for loading less than or equal to 20% of torsional strength. Further, given that stresses associated with axial force, bending, shear and hydrostatic pressure are independent of those generated by torsion, ISO 19902 adopts a linear interaction to determine a reduced value of yield strength for torsional utilization greater than the 20%.

The purpose of the paper is to review relevant design approaches for interaction with beam shear and torsion in tubular members and compare them with the approach adopted in ISO 19902 and, subsequently, ISO 19905-1. Recommendations for improving the ISO 19902 formulae are proposed.

BASICS FOR INCORPORATING BEAM AND TORSION SHEAR

In circular tubular members, the following arise, in part because of the closed nature of the cross-section:

a) shear stresses are concentrated around the neutral axis of the section, a parabolic distribution when considering elastic behaviour but a uniform distribution when considering plastic behaviour with which this paper is primarily concerned – see Figure 1 which shows a typical tubular member plastic distribution of shear and bending stresses both normalised with respect to their yield strengths,

b) torsional warping effects can be neglected and only St Venant torsion need be considered,

c) for interaction between beam and torsional shears, a simple summation can be assumed as the shears act in the same direction on one side (web) of the section,

d) for interaction of beam shear stress and normal stress arising from bending and/or axial forces, the Mises yield function is adopted but is only required for that part of the cross-section where beam shear is present, in the 'webs',

e) for interaction of torsional shear stress and normal stress, again Mises is adopted but since torsional shear is distributed uniformly around the section, it is necessarily applied to the entire cross-section.

BEAM AND TORSIONAL SHEAR INTERACTION

Summing shear stresses arising from beam shear and torsion in circular tubular members has been the basis for their design from at least the early 2000s.

The 2005 edition of AISC 360 uses Equation (1) for interaction between axial force P, bending moment M, beam shear V and torsional shear T:

$$\left(\frac{P_\mathrm{r}}{P_\mathrm{c}}+\frac{M_\mathrm{r}}{M_\mathrm{c}}\right)+\left(\frac{V_\mathrm{r}}{V_\mathrm{c}}+\frac{T_\mathrm{r}}{T_\mathrm{c}}\right)^2 \le 1.0 \tag{1}$$

in which r and c indicate required and available capabilities, respectively. This relationship applies for $T_\mathrm{r}/T_\mathrm{c} > 0.2$. When $T_\mathrm{r}/T_\mathrm{c} \le 0.2$, torsion effects can be ignored and axial, bending and shear interaction are supposedly to be determined from Section H1 of AISC 360. However, Section H1 has no such provisions nor, it seems, does any other provision in AISC 360. Shear-torsion interaction could proceed using the square of the shear summation as shown in Equation (1). However, as pointed out in the AISC 360 Commentary from 2010 onwards, "A more accurate measure is obtained without squaring this combination", i.e., just a sum of the shears.

In EN 1993-1-1:2005, ignoring partial resistance factors, the plastic shear strength $V_\mathrm{pl,Rd}$ is:

$$V_\mathrm{pl,Rd} = \frac{A_\mathrm{v} f_\mathrm{y}}{\sqrt{3}} \tag{2}$$

where A_v = shear area = $2A/\pi$

A = cross-sectional area

f_y = representative yield strength in stress units.

In the presence of St Venant torsion $\tau_\mathrm{t,Ed}$, the plastic shear strength reduces to $V_\mathrm{pl,T,Rd}$:

$$V_\mathrm{pl,T,Rd} = \left(1-\frac{\tau_\mathrm{t,Ed}}{f_\mathrm{y}/\sqrt{3}}\right)V_\mathrm{pl,Rd} \tag{3}$$

Divide by A_v to convert shear force to shear stress τ_b and shear strength to shear yield strength f_v ($= f_\mathrm{y}/\sqrt{3}$):

$$\tau_\mathrm{b} = \left(1-\frac{\tau_\mathrm{t,Ed}}{f_\mathrm{v}}\right)f_\mathrm{v} \qquad \text{i.e., } \frac{\tau_\mathrm{b}}{f_\mathrm{v}} = \left(1-\frac{\tau_\mathrm{t,Ed}}{f_\mathrm{v}}\right)$$

so

$$\frac{\tau_\mathrm{b}}{f_\mathrm{v}}+\frac{\tau_\mathrm{t,Ed}}{f_\mathrm{v}} = 1 \tag{4}$$

i.e., the sum of the shear stresses.

Norsok N-004 considers interaction between bending and shear and bending and torsion but seemingly not between shear and torsion.

The ISO 19902 formulae are similar to those of EN 1993-1-1 but generally expressed in terms of stresses rather than forces. Thus, Formulae (13.2-20) and (13.2-21) ignoring partial resistance factors, rewritten to emphasise this simple addition:

$$\frac{\tau_b}{f_v} + \frac{\tau_t}{f_v} = 1.0 \tag{5}$$

where τ_t = torsional shear stress due to factored actions.

The corresponding ISO FDIS 19905-1 version is found from a combination of Formulae (A.12.5-3), (A.12.5-16) and (A.12.5-17) which simplify to

$$V \leq \frac{AF_y}{\gamma_{R,Tv} 2\sqrt{3}}\left(1 - \frac{T_u}{T_v/\gamma_{R,Tv}}\right) \tag{6}$$

where V = beam shear due to factored actions,
F_y = yield strength in stress units,
$\gamma_{R,Tv}$ = partial resistance factor for torsional and beam shear strengths (= 1.05),
T_u = torsional moment due to factored actions,
T_v = representative torsional strength.

Removing the inequality, converting to stresses using $\tau_b = 2V/A$ and $\tau_t/f_v = T_u/T_v$, recognising $f_v = F_y/\sqrt{3}$ and omitting partial resistance factors gives

$$\frac{\tau_b}{f_v} + \frac{\tau_t}{f_v} = 1.0 \tag{7}$$

as for ISO 19902 – see Equation (5).

BEAM SHEAR/BENDING INTERACTION

Beam shear/bending interaction is here concerned with fully plastic conditions, whether from yield for zones subjected to normal stresses, i.e., tension/compression arising from flexure, or shear yield for zones subjected to purely beam shear, or Mises yield from combinations of normal and beam shear stresses. Of fundamental importance is the area over which the shear is assumed to act. In AISC 360, API RP 2A, N-004 and ISO 19902, shear is assumed to act over half the tubular area A. Alternatively, EN 1993-1-1 takes the shear area for a circular tubular as $2A/\pi$, i.e., $0.637A$, slightly more than the $0.6A$ adopted in BS 5950-1 from where the EN 1993-1-1 shear design formulations have been adopted.

To maximise potential flexural strength, shear is assumed to act on those part of the tubular cross-section adjacent to the neutral axis. In the shear zones, stress interaction is controlled by the Mises equation while beyond these zones, only flexural stresses prevail, limited by yield. Figure 1 illustrates this stress pattern for increasing levels of shear. When shear stress is zero, Figure 1 (a), the cross-section can achieve its full plastic moment capacity M_p. As shear increases, the bending stress in the shear zone decreases correspondingly in accordance with the Mises equation, Figure 1 (b). Figure 1 (c) shows the final stage when shear is at yield and the corresponding bending stress is reduced to zero.

As noted, EN 1993-1-1 adopts a beam shear area A_v of $2A/\pi$. It also does not follow the Mises yield condition for shear-normal stress interaction in the shear zones, instead it prescribes a reduced yield strength f_{yr} for these zones, as used previously in BS 5950-1, of:

$$f_{yr} = (1 - \rho) f_y \tag{8}$$

where $\rho = 0$ for $\frac{V_{Ed}}{V_{pl,Rd}} < 0.5$

$$\rho = \left(\frac{2V_{Ed}}{V_{pl,Rd}} - 1\right)^2 \quad \text{for } \frac{V_{Ed}}{V_{pl,Rd}} \geq 0.5 \tag{9}$$

and V_{Ed} = design value of shear force

$V_{\text{pl,Rd}}$ $= A_v(f_y/\sqrt{3})/\gamma_{M0}$

γ_{M0} = partial resistance factor (= 1.0).

Outside the shear zones, bending strength equals yield strength. In Equation (9), the shear force variables V_{Ed} and $V_{\text{pl,Rd}}$ can be readily replaced by their stress equivalents τ_b and f_v.

Plots of these two shear-bending interactions are presented in Figure 2. Figure 2 (a) shows normalised bending strength versus shear stress normalised by shear yield while Figure 2 (b) shows normalised bending strength versus shear force normalised with respect to the EN 1993-1-1 full shear strength capacity: the EN value was selected because it is the larger. Clearly they are significantly different in shape despite ostensibly addressing the same problem, i.e., shear-bending interaction in circular tubulars. To help understand the difference, Figure 2 (c) was generated. It shows how the reduced value of yield strength in the shear zones varies with the shear stress ratio.

The following observations can be made:

a) 2 (a) - when shear stress equals half its yield value, just as Equation (9) becomes effective, EN 1993-1-1 allows full plastic moment while, for the Mises condition, plastic capacity is reduced but only by 4%,

b) 2 (b) - because the EN 1993-1-1 shear area is larger than that used for the Mises condition, its full shear capacity is $(2A/\pi)/(0.5A) = 1.273$ times that available to ISO 19902,

c) 2 (a) - in contrast, under full shear yield conditions, the smaller EN 1993-1-1 flexural area results in a bending capacity of only 76.4% of that under Mises,

d) 2 (a) - for the Mises interaction, even when the shear zones are fully utilised in shear, the flexural capacity is still 70.7% of the fully plastic moment,

e) 2 (a) - both demonstrate why the effect of shear on tubular flexural capacity can be ignored for shear up to 0.7 of shear yield as flexural capacity is still 90% of M_p as shear utilization approaches 75%

f) 2 (c) – the EN formulation departs significantly from the Mises yield function. When the shear stress ratio is 0.6, the EN reduced yield strength is 20% greater than that determined by Mises while for shear stress ratios approaching 1.0, the EN value is only 25% of the Mises value.

The effect of the difference in shear areas was examined further by adopting the Mises function in place of Equation (9) for the EN shear area and plotting the outcomes as normalised moments versus shear stress ratio and versus shear force ratio – see Figures 3 (a) and (b). Compared with the corresponding plots in Figures 2 (a) and (b), the effect of adopting the Mises function to determine reduced values of yield in the shear zone is seen to be significant. For shear ratios up to 0.7, both plots given relatively similar outcomes. Beyond 0.7, Figure 3 (a) highlights the effect of a larger available bending area while Figure 3 (b) demonstrates the effect of the larger EN shear area.

The lower bound theorem would seem to suggest either shear area assumption could be appropriate provided the assumed stress distributions nowhere exceed yield and they are in equilibrium with the applied forces. Different combinations of bending and beam shear would require different proportions of zones in flexure to zones in shear.

It is useful to compare these two relationships with others used for the design of tubular members. AISC 360 uses Equation (1) with $P_r/P_c = T_r/T_c = 0.0$ – see Figure 4.

N-004 adopts the following (see Figure 4):

$$\frac{M_{\text{Sd}}}{M_{\text{Rd}}} = \left(1.4 - \frac{V_{\text{Sd}}}{V_{\text{Rd}}}\right)^{0.5} \qquad \text{for } \frac{V_{\text{Sd}}}{V_{\text{Rd}}} \geq 0.4$$

$$\frac{M_{\text{Sd}}}{M_{\text{Rd}}} = 1.0 \qquad \text{for } \frac{V_{\text{Sd}}}{V_{\text{Rd}}} < 0.4 \qquad (10)$$

where M_{Sd} = design bending moment

M_{Rd} = plastic moment strength for compact sections and ignoring the partial resistance factor

V_{Sd} = design shear force

V_{Rd} = shear yield strength over half cross-sectional area.

ISO 19902 first edition provided conventional equations for determining utilization of tubulars subjected to beam and torsional shears but no formulae for interaction between the two or with other stresses. This was rectified in the second, 2020, edition. The 2020 approach is to introduce a reduced representative bending strength in the presence of shear, here without the partial resistance factor and plotted in Figure 4:

$$\frac{f_{b,v}}{f_b} = 1.0 \qquad \text{if } \frac{\tau_b}{f_v} \leq 0.7$$

$$\frac{f_{b,v}}{f_b} = 0.7 + 1.2\,\frac{\tau_b}{f_v}\left(1 - \frac{\tau_b}{f_v}\right) \qquad \text{if } \frac{\tau_b}{f_v} > 0.7 \tag{11}$$

From Figure 4, it can be seen that AISC 360 is particularly conservative relative to the other interactions. In the high shear region, $\tau_b/f_v > 0.7$, ISO 19902 most closely approximates the Mises condition whereas both EN 1993-1-1 and N-004 underestimate flexural strength. In the medium shear region, $0.5 < \tau_b/f_v \leq 0.7$, N-004 continues to underestimate flexural strength while ISO 19902 and EN 1993-1-1 overestimate flexural capacity.

TORSION/BENDING INTERACTION

Because torsional stress acts on the entire circumference of a tubular, its presence limits the maximum value of all other stresses. Stress maxima are usually accounted for by the Mises yield criterion as done above for beam shear/bending interaction. Thus, a reduced value of yield strength in the presence of torsion is:

$$f_{yr} = \sqrt{\left(1 - \left(\frac{\tau_t}{f_v}\right)^2\right)}\, f_y \tag{12}$$

This is the same formulation as adopted in N-004. For AISC 360, the relevant relationship is Equation (1) with the axial and shear terms omitted. For EN 1993-1-1 there appears to be no effect of torsion in the absence of shear. ISO 19902 ignores torsion when less than or equal to 20% of shear yield. A reduced yield strength is used otherwise given by, with the partial resistance factor omitted:

$$f_{y,t} = \left(1 - \frac{\tau_t}{f_v}\right) f_y \tag{13}$$

These interactions are shown in Figure 5. Presuming the EN 1993-1-1 approach has been interpreted correctly, it is clearly non-conservative seemingly allowing simultaneous full utilization in both torsion and flexure. In contrast, the ISO 19902 approach is particularly conservative while AISC 360 formula approaches the Mises solution from the safe side.

BEAM SHEAR/TORSION/BENDING INTERACTION

The Mises interaction for beam shear, torsion and bending was determined on the following basis:

a) in flexural zones, yield strength was reduced in the presence of torsion τ_t using the Mises function shown in Equation (12),

b) in shear zones, yield strength was reduced in the presence of beam shear τ_b and torsion τ_t using the following Mises function on the grounds that, on one web, beam shear and torsional shear are additive,

$$f_{yr} = \sqrt{\left(1 - \left(\frac{\tau_b + \tau_t}{f_v}\right)^2\right)}\, f_y \tag{14}$$

The resulting beam shear/moment interaction curves are shown in Figure 6 (a) for levels of torsion equal to 0%, 20% and 40% of shear yield strength. In the absence of torsion, the curve is identical to that shown in Figure 2 (a). For 20% and 40% torsion, as expected, maximum moment occurs when shear is zero with values equal to $\sqrt{1 - 0.2^2} = 0.98$ and $\sqrt{1 - 0.4^2} = 0.917$ of M_P, the plastic moment capacity. With increasing shear, the moment reduces in accordance with Equation (12) until full shear yield is reached in the web zones (in one web to be precise) resulting from the simple summation of beam shear and torsional shear, i.e., 0.8 of shear yield for 20% torsion and 0.6 shear yield for 40% torsion. The corresponding moments are 0.693 and 0.648 of M_P compared with 0.707 of M_P in the absence of torsion.

Also shown in Figure 6 (a) are corresponding curves for EN 1993-1-1 and AISC 360. For EN 1993-1-1, the significant difference in shear-bending interaction compared with the Mises formulation has already been discussed in detail – see Figures 2 and 3. Its use of simple addition to account for shear-torsion interaction leads to the same values of maximum shear as Mises of 0.8 and 0.6 given 20% and 40% torsion. However, increase in torsion does not lead to any reduction in flexural strength because, as seen in Figure 5, EN 1993-1-1 seemingly has no interaction between torsion and flexure.

The range of torsion values considered for the AISC 360 interactions are 0-20%, 21% and 40% because AISC 360 allows torsion to be ignored if less than or equal to 20% of its yield strength. In the absence of flexure, beam shear strength is overstated by 25% when 20% torsion is present. For torsion levels of 21% and greater, simple addition of the shears applies so the maximum beam shear strengths match those of Mises. In the absence of beam shear, bending strength is reduced in accordance with Equation (1). For torsion less than or equal to 20%, this leads to similar bending strengths as Mises. For greater levels of torsion, Figure 5 demonstrates the greater reduction in AISC 360 bending strength compared with that of Mises so, for 21% and 40% torsion, moment capacity is $1 - 0.21^2 = 0.956$ and $1 - 0.4^2 = 0.840$ of M_P. The conservative interaction for intermediate values of beam shear and flexure has already been noted.

In Figure 6 (b), Mises interaction is compared with that of Norsok N-004 and ISO 19902. As seen in Figure 5, N-004 torsion-bending interaction equates to the Mises condition so, in the absence of beam shear, N-004 flexural capacity equates to that of Mises. However, as noted above, there appears to be no N-004 interaction between beam and torsional shears thus, full shear yield strength is possible whatever the level of torsion. ISO 19902 uses simple addition to account for the effect of beam and torsional shear interaction but, like AISC 360, ignores torsion up to 20% of shear yield. Hence, like the AISC 360 torsion values seen in Figure 6 (a), those for ISO 19902 in Figure 6 (b) are 0-20%, 21% and 40%. Thus, beam shear strength is overstated by 25% for torsion up to 20% of shear yield. The ISO 19902 conservative linear reduction in bending strength with torsion, as given by Equation (13) and seen in Figure 5, is reflected here as bending strength falls well below the Mises values except for torsion of 20% or less when flexural strength is overstated by up to 2%.

BEAM SHEAR/TORSION/AXIAL FORCE INTERACTION

Proceeding as for the Mises beam shear, torsion and bending interaction but replacing bending by axial force results in the plots shown in Figure 7 (a). In the absence of torsion, given half the cross-sectional area sustains axial force, when full shear is present, the axial capacity is half its fully plastic capability. When beam shear is zero, torsional shear reduces axial capacity to 0.980 and 0.917 of its full value. Beam and torsional shear simply sum to reduce shear capacity to 80% and 60% of shear yield in the presence of 20% and 40% torsion.

For EN 1993-1-1, similar to the outcome presented in Figure 5, there is no effect of torsion in the absence of shear and, although bending and shear interaction accounts for the presence of torsion, bending shear and axial force interaction does not. Thus, EN 1993-1-1 axial strength is non-conservative for all combinations of shear and torsion except when shear is high and torsion is low. N-004 also just considers shear, bending and torsional interaction, no shear, axial force and torsional interaction.

Given the AISC 360 formula governing beam shear, axial force and torsion interaction, i.e., Equation (1), is effectively identical to that governing beam shear, bending and torsion interaction, the corresponding plots can be expected to be identical to those shown in Figure 6 (a), which is the case as seen in Figure (7). The AISC 360 plots for torsion in excess of 20% are conservative with respect to the corresponding Mises plots but for torsion just less than 20%, AISC 360 is non-conservative for high levels of beam shear,

The ISO 19902 formulae for beam shear, torsion and axial force interaction are similar to those for shear, torsion and bending interaction, as can be seen by comparing the relevant plots in Figure (7) with those in Figure 6 (b)). For torsion in excess of 20% utilization, axial capacity is underestimated particularly at low levels of beam shear. However, ISO 19902 is notably non-conservative for torsion less than or equal to 20% of yield especially for higher levels of beam shear.

FINDINGS

Four standards that could be used for the plastic design of stocky circular tubulars for offshore application when torsion is present have been examined through consideration of interaction with beam shear, bending moment and axial force: they are:

i) EN 1993-1-1

ii) AISC 360

iii) Norsok N-004

iv) ISO 19902.

Interaction curves are developed and compared with those generated by assuming the Mises yield condition provides an appropriate basis for correctly assessing strength under these combined loading conditions.

All assume the tubular cross-section is divided into shear zones and normal zones. In shear zones (webs), interaction between beam shear and torsional shear is generally taken as the simple addition of the two shears except in N-004 which does not address this combination.

All standards except EN 1993-1-1 assume the web area to be half the cross-sectional area. EN 1993-1-1 assumes ($2/\pi = 0.637$) of the cross-sectional area. Thus, designs to EN 1993-1-1 can sustain 27.4% more shear loading than the other standards but only 76.4% of the bending capacity. Further, EN 1993-1-1 does not adopt the Mises equation for interaction between shear and normal stresses, instead it assumes a form on interaction that leads to greater bending capacity for shear utilization in the range 50-70% of shear yield but reduced bending capacity for shear utilizations between 80% and 100%. Because of the difference in web area, the beam shear-moment interaction curves demonstrate significant difference depending on whether the shear is expressed in stress or force terms.

The AISC 360 beam shear-moment interaction is particularly conservative while the others approximate Mises although N-004 underestimates flexural strength for beam shear utilization greater than 70%.

Torsion-moment interaction is not done well by any standard, particularly ISO 19902 which uses a linear equation to reduce yield strength in the presence of torsion when the Mises formulation should have been used. N-004 does not have any relevant equation while EN 1993-1-1 does in the presence of shear, but which seems not to apply when beam shear is zero. The AISC 360 torsion-moment interaction is similar to the beam shear-moment interaction and, as such, provides the solution closest, conservatively, to Mises.

Interaction between beam shear, torsion and bending is complicated by the cut-off in AISC 360, and subsequently adopted in ISO 19902, to ignore torsion when less than or equal to 20% utilization. AISC 360 can be non-conservative for torsional utilization between 0 and 20% limited to beam shear in excess of 80% with bending utilizations less than 40%. On the other hand, ISO 19902 is non-conservative for all combinations of beam shear and moment for torsional shear utilization up to 20% although conservative for higher levels of torsion especially with respect to flexural capacity. The 20% cut-off in ISO 19902 should be removed.

Neither EN 1993-1-1 nor N-004 have a cut-off. However, the absence of any interaction between torsion and bending in EN 1993-1-1 means that this standard can be non-conservative for low-intermediate levels of beam shear when torsion utilization is more than 20%. N-004 correctly quantifies the effect of torsion on bending but has no beam shear-torsion interaction so overestimates combined beam shear-bending strength for torsion utilization greater than 20%, independent of beam shear utilization, and particularly so under high beam shear utilization.

When axial force replaces bending moment, for shear at 100% utilization, maximum axial capacity is 50% of full utilization whereas bending is 70.7%. AISC 360 does not differentiate between bending moment and axial force so its interaction curves for beam shear, torsion and bending and beam shear, torsion and axial force are identical. Thus, AISC 360 is a little less conservative for beam shear, torsion and axial force interaction except for torsion up to 20% utilization when it can be unconservative particularly for beam shear just above 80% utilization. EN 1993-1-1 does not address interaction between beam shear, torsion and axial force so cannot be used when torsion is present. For some reason, ISO 19902 adopts the same interaction formula for axial force-shear interaction as it does for bending-shear interaction. For the former, the first term in the ISO 19902 formula should have been 0.5 rather than 0.7. As for beam shear, torsion and bending interaction, ISO 19902 is non-conservative for torsional shear utilization up to 20% further confirming the need to remove the 20% cut-off.

CONCLUSIONS AND RECOMMENDATIONS

Of the standards reviewed, only ISO 19902 provides for the complete combination of forces to which circular tubulars used offshore can be subjected including hydrostatic pressure: ISO 19905-1, which adopts the ISO 19902 tubular member formulations, is similar but does not address pressure. Excluding pressure effects, only AISC 360 and ISO 19902 provide for interactions between beam shear, torsion, bending moment and axial force. However, while AISC 360 does this using one simple expression, ISO 19902 provides several formulae to address all possible combinations. Unfortunately, aspects of the ISO 19902 formulations suffer weaknesses, as follows:

i) ignoring up to 20% torsion is non-conservative and should be removed,

ii) the linear interaction for reducing yield strength in the presence of torsion is unnecessarily conservative and should be replaced by the Mises equivalent,

iii) the formulae accounting for shear and axial force interaction gives 0.7 as the available axial capacity under full beam shear utilization: it should be 0.5.

AISC 360 also ignores up to 20% of torsion: this is non-conservative and should not be applied in the case of tubulars. In line with some other considered standards, AISC 360 simply sums beam and torsional shears to quantify their combined effect. However, unless a designer knows the corresponding Commentary, the AISC 360 equation would encourage the use of a non-conservative square of the sum of shears instead of just the simple sum. The AISC 360 general equation involves linear consideration of normal forces due to bending moment and axial force combined with the square of the sum of shears. This is always quite conservative.

EN 1993-1-1 also sums beam and torsional shears. However, its combined beam shear and bending moment formulation departs significantly from a Mises approach leading to higher flexural capacity for intermediate levels of beam shear utilization and lower flexural capacity for higher levels of beam shear utilization. Further, EN 1993-1-1 adopts a web shear area of $2/\pi$ of the cross-sectional area instead of 0.5 as adopted by the other standards. This 27.3% larger web area thus provides greater shear force capacity but correspondingly smaller flexural and axial force capability than other standards. Apart for resorting to NLFEA, there seems to no other obvious way to determine which of these areas is correct because, according to the lower bound theorem, both seem to be correct. Although, EN 1993-1-1 addresses beam shear, torsion and bending interaction, it does not address beam shear, torsion and axial force interaction.

N-004 does not consider beam shear and torsion interaction. Its beam shear-moment linear interaction is somewhat conservative for high shear utilization. Beam shear, moment and torsion interaction is determined by reducing bending strength in the presence of torsion but the absence of beam shear-torsion interaction means flexural strength is excessive in high beam shear conditions. N-004 does not address any shear-axial force interaction.

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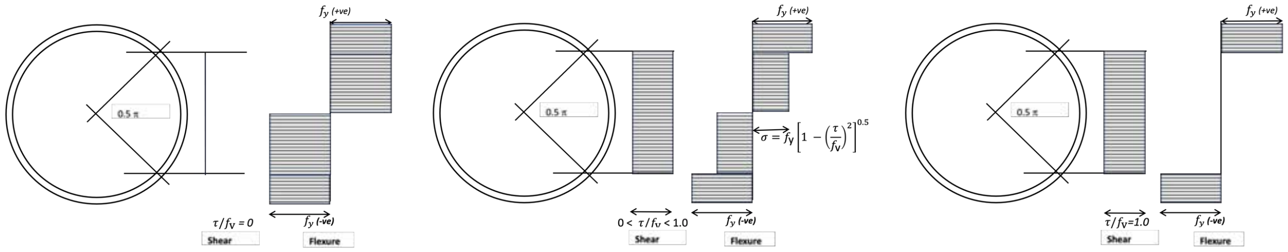
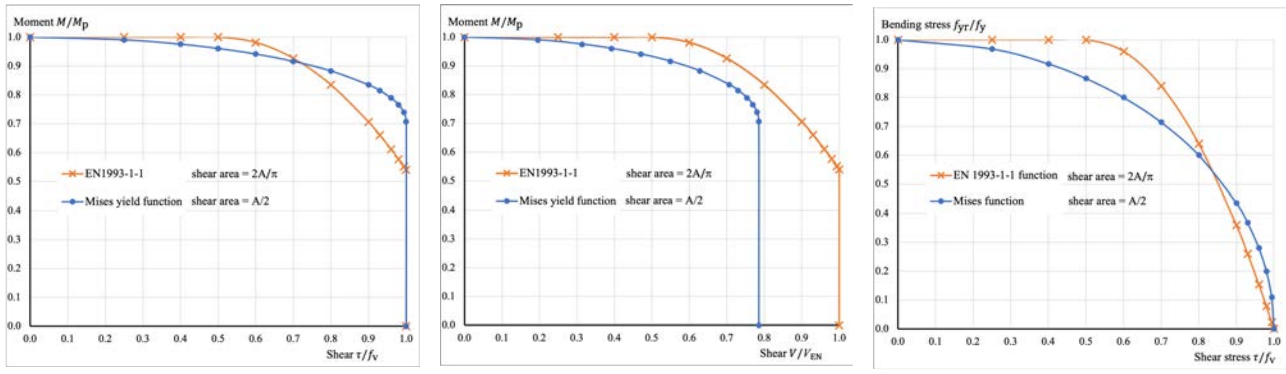
[5] ISO/FDIS 19905-1 Oil and gas industries including lower carbon energy – Site-specific assessment of mobile offshore units – Part 1: Jack-ups: elevated at a site.



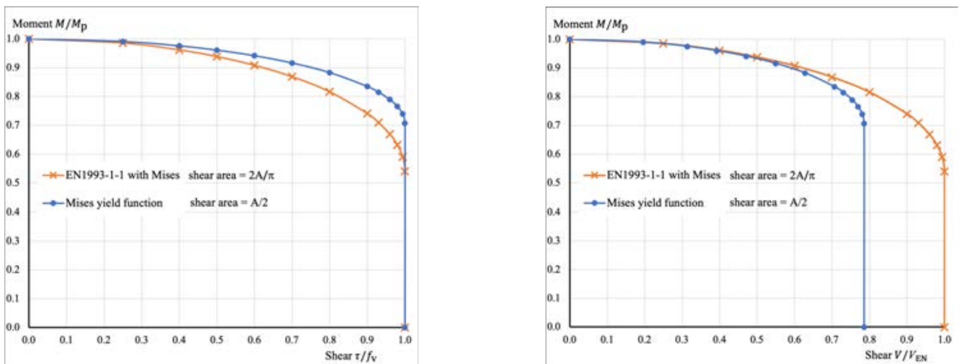
(a) Zero shear (b) Shear < shear yield (c) Shear at shear yield

Figure 1: Typical plastic distribution of normalised shear and bending stresses



(a) Shear stress v moment (b) Shear force v moment (c) Reduced yield strength functions

Figure 2: EN 1993-1-1 and Mises Shear-Moment Interaction Curves



(a) Shear stress v moment (b) Shear force v moment

Figure 3: Shear-Moment Interaction Curves - Effect of Adopting the Mises Function for EN Shear Area

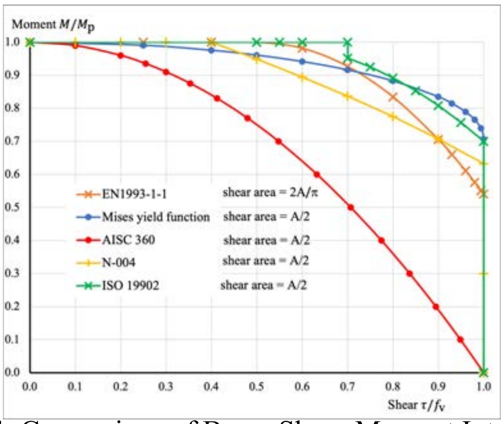


Figure 4: Comparison of Beam Shear-Moment Interaction Curves

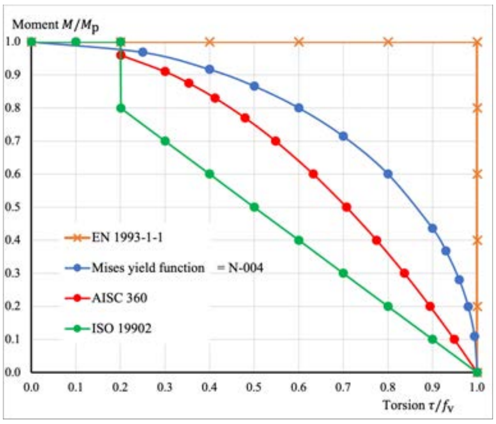
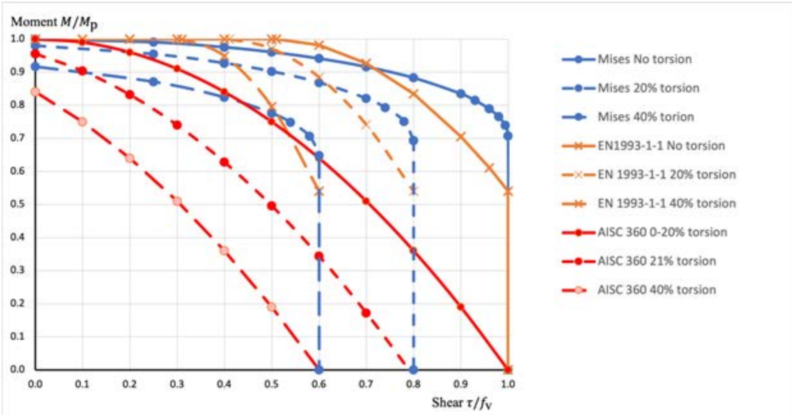
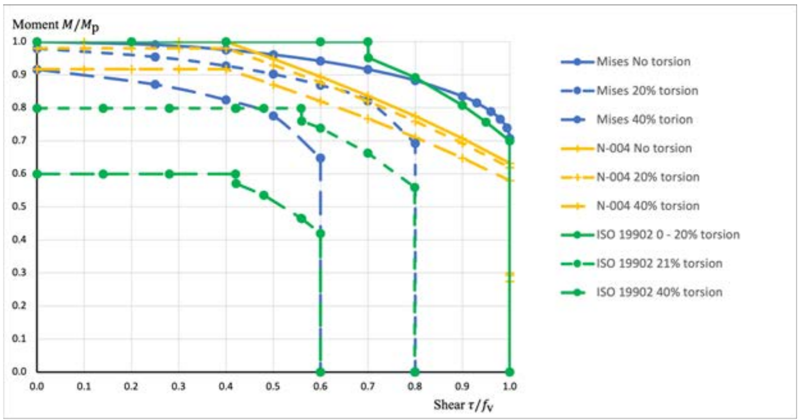


Figure 5: Comparison of Torsion-Moment Interaction Curves



(a) Mises, EN 1993-1-1 and AISC 360



(b) Mises, N-004 and ISO 19902

Figure 6: Comparison of Beam Shear-Torsion-Moment Interaction Curves

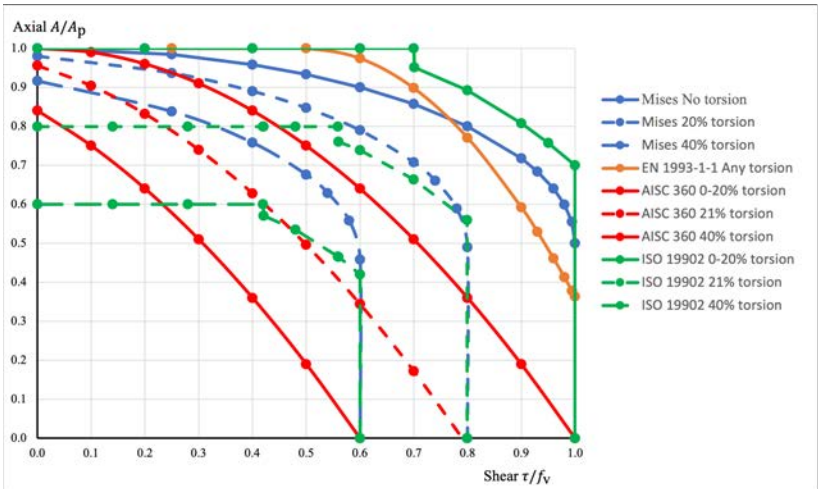


Figure 7: Comparison of Beam Shear-Torsion-Axial Force Interaction Curves