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Reliability of Welded Tubular K-Connection Resistance Expressions

by J.A. Packer

Since round or circular hollow sections exist in both offshore and onshore structures, proposed expressions for the static resistance of welded connections between such members are much more numerous than for connections between square and rectangular members. The draft (2003) revisions for the API RP2A-WSD 22nd. edition, from the U.S. Offshore Tubular Joints Task Group (OTJTG 2003), represent the latest such development. This document can be compared to the existing formulas advocated by IIW (1989), CIDECT Design Guide No.1 (Wardenier et al. 1991) and Eurocode 3, which are all the same and are also recommended by Packer and Henderson (1997). The latter, in turn, are currently adopted in Chapter K of the AISC draft (2005) Specification.

Different formulas are derived by researchers from different databases of experimental and numerical (FE) tests. The published database and failure criteria behind the IIW recommendations for circular tube welded K-connections consists of 676 planar and 219 multiplanar test (experimental + FE) results (Makino et al. 1996), with an earlier version compiled by Packer and Kremer (1985). An evaluation of the AWS D1.1 design equations for tubular K-connections, using the IIW database, showed these to be less accurate than the IIW (or AIJ) counterparts and also have some deficiencies (Kurobane and Ochi 1994). The database behind the recent OTJTG recommendations for K-connections consists of 601 planar, axially-loaded test (experimental + FE) results (OTJTG 2003, Table C.4.3-1).

With structural design recommendations for offshore structures care has to be taken in transposing design equations to normal building structures, as the failure probabilities allowed for elements in offshore structures - as well as the loading criteria - can be significantly different to those used in buildings. Nevertheless, the "lower bound ultimate strength" design rules for "Simple Joints" in Clause 4.3 of the OTJTG recommendations are correlated to the OTJTG database in Table C.4.3-1 and, for axially-loaded K-connections, the statistical parameters for the (Actual/Predicted) capacities are:

- For the experimental database: Mean Bias = 1.34 COV = 0.17
- For the numerical (FE) database: Mean Bias = 1.14 COV = 0.11

The classical, simple version for the LRFD/LSD resistance factor (ϕ) of elements in **buildings**, under typical live and dead load combinations, is given by:

$$\phi = (\text{Mean Bias}).\exp[-0.55.(\text{Safety Index}).\ \text{COV}] \qquad \text{..........}\ (1)$$

wherein the safety index for members and welded connections (but not connectors) is generally taken as 3.0. A more detailed reliability analysis, taking into account mechanical and geometrical property variations will typically show this expression to be conservative nowadays, because of the significant positive bias with the yield stress. For the above OTJTG statistical parameters, this would imply that the cited new "lower bound ultimate strength" equation for K-connections in Clause 4.3 could be multiplied by a ϕ factor, for LRFD/LSD of buildings, of 1.01 (based on experimental data) or 0.95 (based on numerical data). Thus, the OTJTG "lower bound ultimate strength" formula almost requires a resistance factor of unity. Even if one took a $\phi = 0.95$ then, by the AISC conversion process, this would entail adopting a safety factor (Ω) of $1.5/\phi = 1.58$ for Allowable Stress Design (ASD) or Working Stress Design (WSD). It is interesting to note that the OTJTG

Report actually recommends a Factor of Safety (FS) for "Simple Joints" in Clause 4.3, *for offshore structures*, of 1.60.

If the OTJTG Report equation (4.3-1a) is actually an accurate model of welded tubular K-connection capacity then, based on the above, the approximate factored resistance for building design could be given by (using $\phi = 1.0$ as determined above):

$$P_r \sin\theta = F_y T^2 \, Q_u Q_f \quad \text{..........} \quad (2)$$

In Equation (2) above, T is the thickness of the chord member, F_y is the yield stress of the chord member, Q_u is given in Table 4.3-1 of the OTJTG Report and, for simplicity, the chord stress effect factor Q_f can be taken as unity at this stage.

By comparison, the K-connection factored resistance given by IIW/CIDECT and used by AISC in equation (K2-6) of the draft 2005 Specification, with the resistance factor inserted, is (using similar notation to API):

$$P_r \sin\theta = F_y T^2 \, [1.8 + 10.2\beta] \, Q_u Q_f \quad \text{..........} \quad (3)$$

This is also the factored resistance equation given in Packer and Henderson (1997), page 80, with the "resistance factor" already inserted.

It is now possible to explore the relationship between the two K-connection "factored resistance" equations (2), by API, and (3), by IIW to see how they differ quantitatively for various connection parameters. In doing so, one can set $Q_f = 1.0$ for both equations, so the comparison is manageable. Thus, one can investigate the factored resistance ratio (IIW/API) = (Equation3)/(Equation 2), for a matrix of connection non-dimensional parameters. Within the validity ranges of both the IIW and API expressions, the connection parameters have been studied over the following range:

- For γ = 10, 15, 20 and 25
- For β = 0.2, 0.3, 0.4, 0.7 and 1.0
- For g/D = 0.05, 0.15, 0.25, 0.5.

The results of this (IIW/API) resistance ratio, indicating some key trends, are shown in the following graphs. To know that the AISC equation (K2-6) was erring on the conservative side, relative to the API model, values of (IIW/API) $\leq$ 1.0 would supply comfort. This is generally the case, except for low β values around 0.2 to 0.3.

In assessing these comparisons, one should bear in mind:

1. The API formula range of validity for γ is from 10 to 50, whereas the corresponding IIW validity range is from no lower limit up to 25. This illustrates the typical difference in chord slenderness ranges for offshore and onshore structures. Recent tubular steel highway and railway bridges in France, Switzerland and Germany have even had γ values for the chord in the range of 5 to 6. The focus on more slender chord (large γ) sections influences the database in the API study. The K-connection strength function Q_u is capped at $\gamma = 20$ by API (in Table 4.3-1) even though.......(to quote from the Commentary to Clause 4.3.3)......"The API/EWI FE study..... shows a dependence of the basic strength factor Q_u on γ (as well as β) which is more obvious at large γ ..."

   Thus, disparities in trends with γ, between IIW and API, should not carry too much weight.

2. The API recommendations are geared towards gapped connections, and the Commentary to Clause 4.4 on "Overlapping Joints" indicates that the application of the K-connection formula to overlapping joints

is still tentative.....(to quote)......"A relatively complete summary of the problems with the existing guidances and the background database can be found in Ref. 44. The guidance recommended here has been based on the MSL JIP results (Ref.5)". Thus, the OTJTG appear not to have covered overlapped K-connections in their database at all, in the current project. It appears that $g/D = +0.05$ is the lowest gap ratio covered. The IIW database includes gapped and overlapped K-connections, and the formula is oriented to cover this complete range.

Thus, disparities in trends at low gap or g/D values, between IIW and API, should not carry too much weight.

3. The IIW resistance still significantly exceeds the API resistance, for low β values. Until this anomaly is resolved it may prove wise to exercise caution, albeit perhaps unwarranted, and restrict the range of application of the IIW (and CIDECT, Eurocode 3, CISC and AISC) K-connection, so that the "IIW resistance" is always less than the "API resistance".

Thus, it is recommended to change the K-connection range of validity to $\beta \geq 0.4$.

This would make the range of validity for round HSS K-connections similar to that for square/rectangular HSS K-connections.

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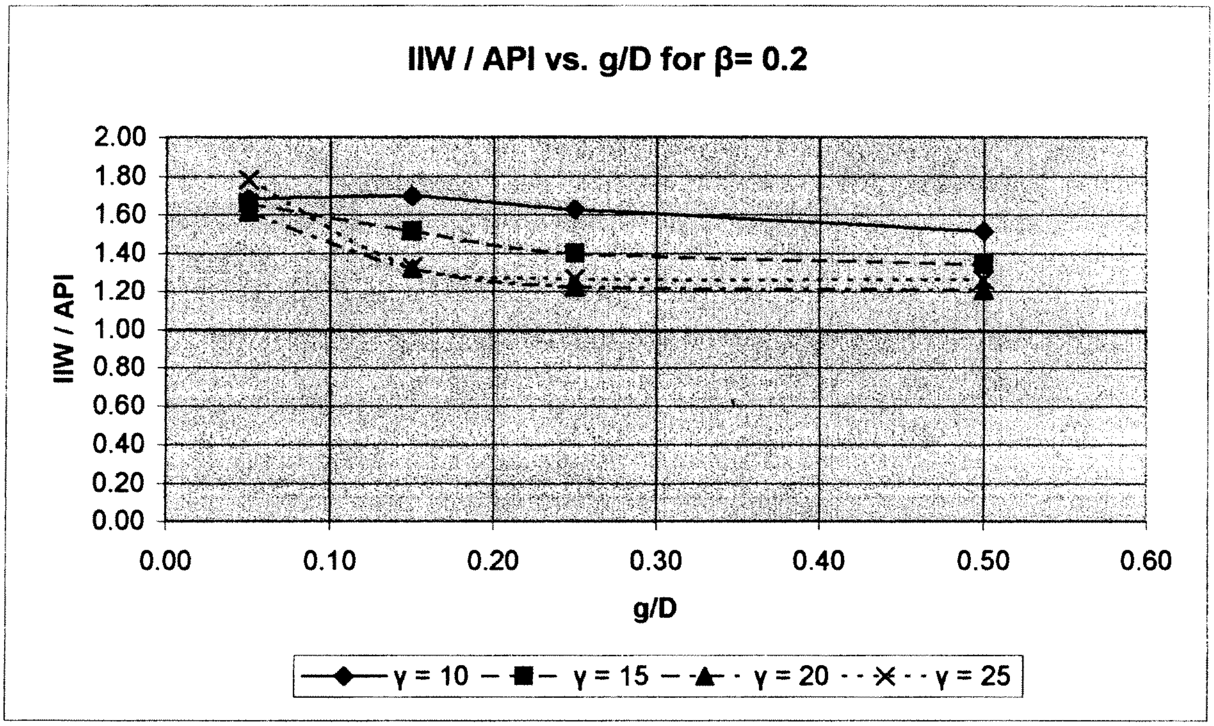
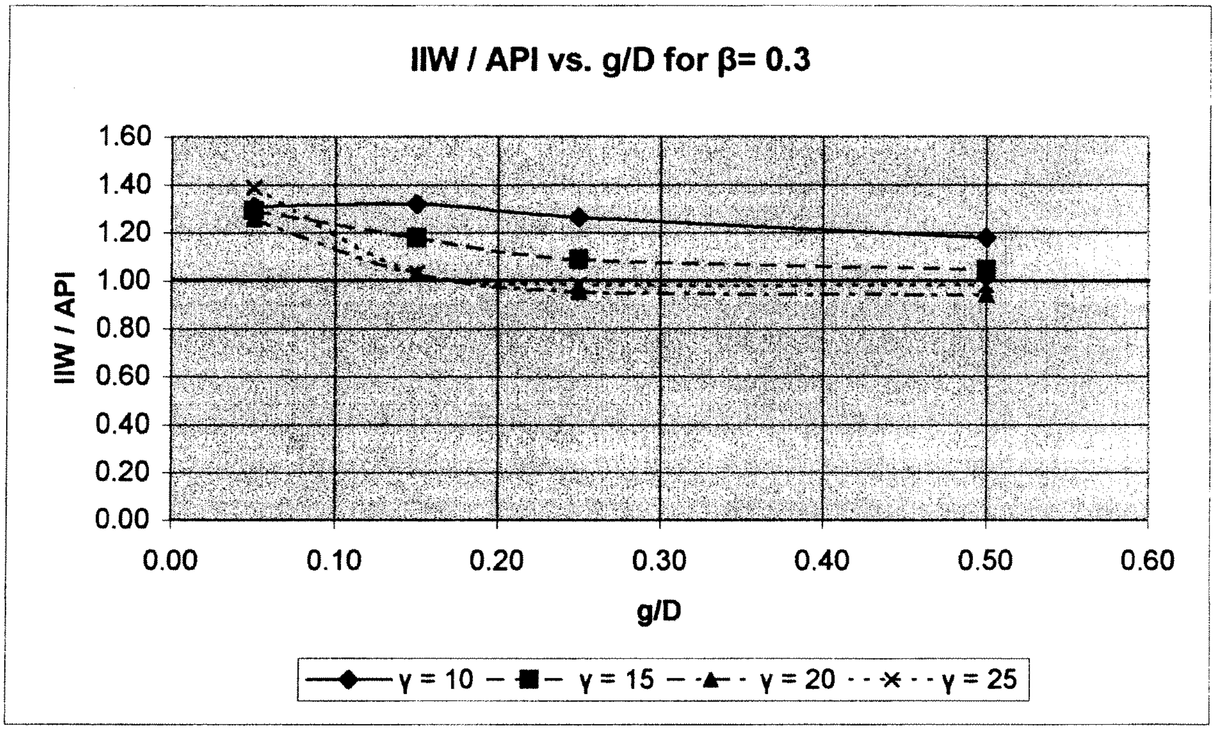

IIW / API vs. g/D for β= 0.2
2.00
1.80
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
IIW / API
0.00
0.10
0.20
0.30
0.40
0.50
0.60
g/D
γ = 10
γ = 15
γ = 20
γ = 25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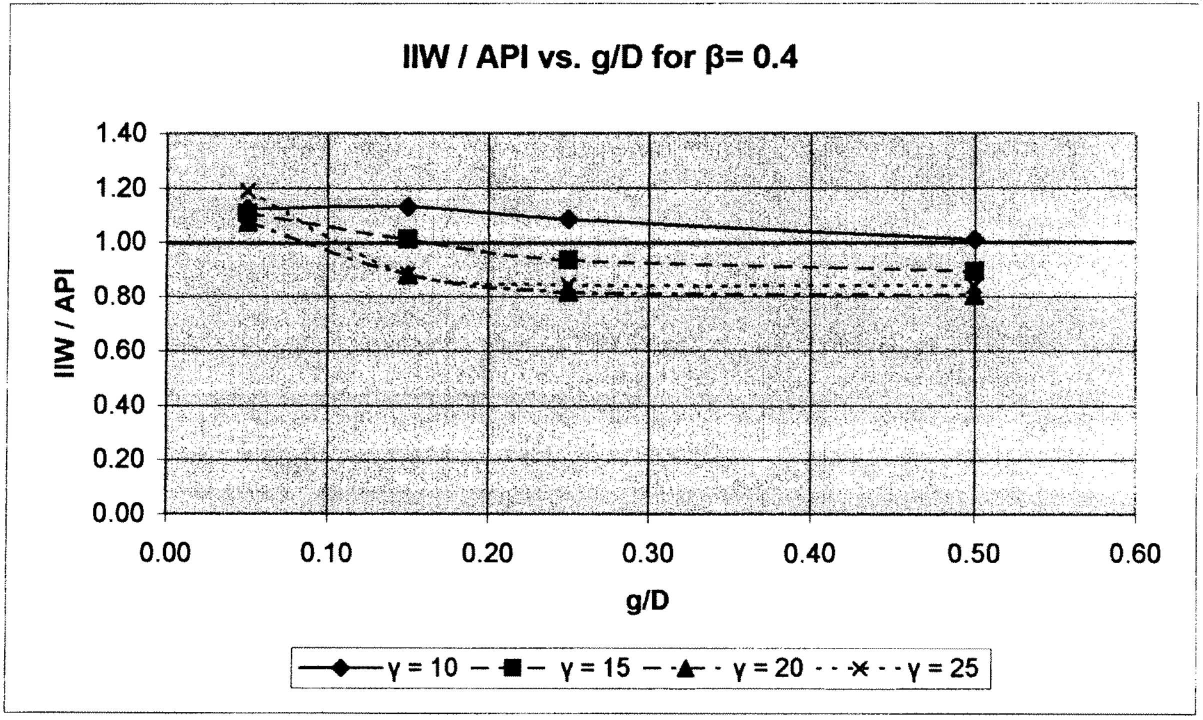
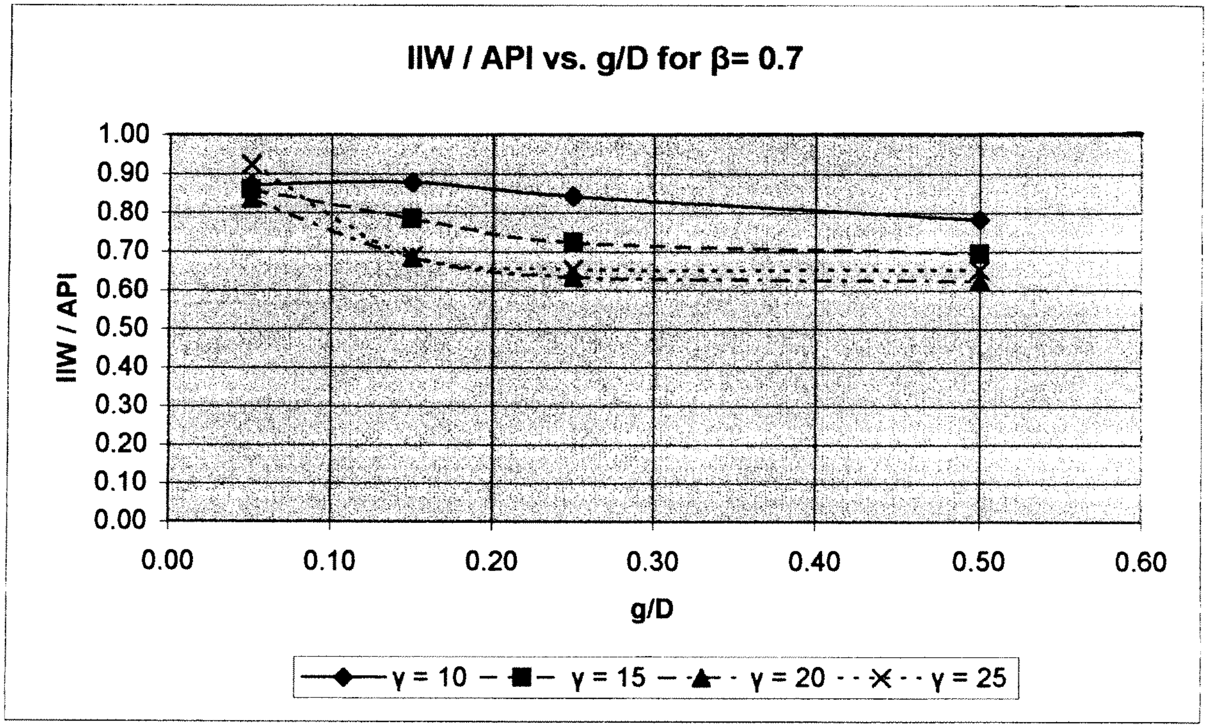
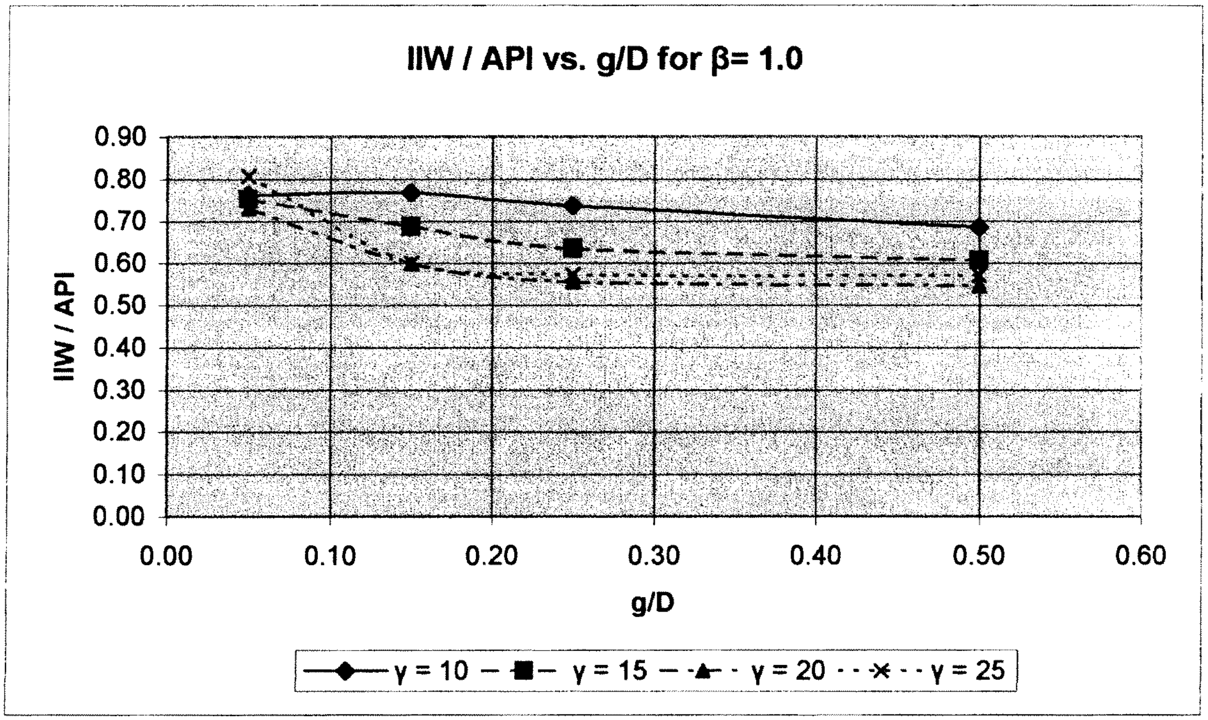
1.60
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
IIW / API
0.00
0.10
0.20
0.30
0.40
0.50
0.60
g/D
γ = 10
γ = 15
γ = 20
γ = 25


IIW / API vs. g/D for β= 0.4
IIW / API
1.40
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
g/D
γ = 10
γ = 15
γ = 20
γ = 25


IIW / API vs. g/D for β= 0.7
IIW / API
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
g/D
γ = 10
γ = 15
γ = 20
γ = 25


IIW / API vs. g/D for β= 1.0
IIW / API
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0.00
0.10
0.20
0.30
0.40
0.50
0.60
g/D
γ = 10
γ = 15
γ = 20
γ = 25