Strength, stiffness and nonlinear behaviour of simple tubular joints

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Strength, Stiffness and Nonlinear Behaviour of Simple Tubular Joints

Résistance, rigidité et comportement non linéaire d'assemblages tubulaires simples

Festigkeit, Steifigkeit und nicht-lineares Verhalten von einfachen Knotenpunktsverbindungen aus Rundhohlprofilen

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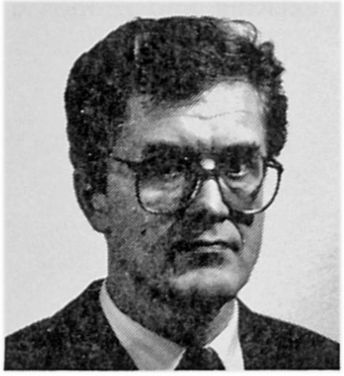
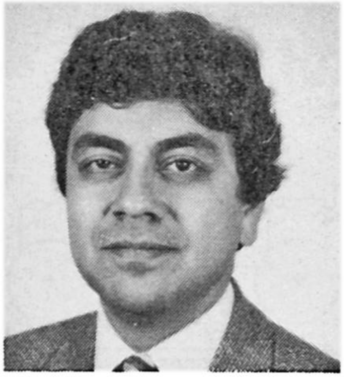
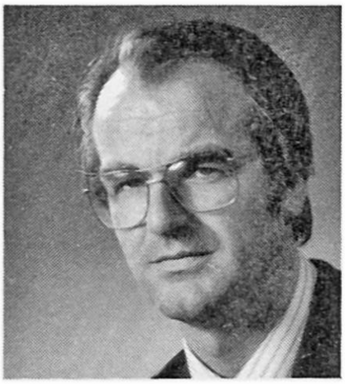


Pentti Mäkeläinen, born 1944, obtained his engineering degree and his doctoral degree at Helsinki University of Technology. Since 1969 he has been working in the Department of Civil Engineering as a research assistant, a lecturer, an associate professor and an acting professor of Structural Mechanics and of Steel Structures.



Ram Puthli, born 1944, graduated in Civil Engineering from I.I.T. Kharagpur, India in 1964. He obtained his M.Sc (Structures) from Manchester University and Ph.D. from Surrey University. He has ten years experience in Industry and twelve years in Research. He has been involved in research at TNO-IBBC since 1979.



Frans Bijlaard, born 1947, graduated as Civil Engineer at the Technical University Delft. For the last ten years he has been concerned with research on stability and connections in steel structures. At present he is Head of the Department of Steel Structures of the TNO Institute for Building Materials and Structures.

SUMMARY
The present work describes a wide investigation on joint behaviour. Semi-analytical formulae are established for initial stiffness, strength under single and combined loading, and the secant stiffness at any load up to collapse. This information is sufficient to plot the complete non-linear behaviour until collapse and to determine the stiffness at working loads. All this work has been checked against experimental data from a large data bank. The work on simple multibraced joints is incomplete because of the absence of experimental data for these joints.

RÉSUMÉ
Cette étude présente une vaste recherche sur le comportement d'assemblages. Des formules semi-analytiques donnant la rigidité initiale, la résistance pour des charges simples et combineés ainsi que la rigidité sécante, ont été établiés pour des charges allant jusqu'à la limite de rupture. Cette information suffit pour décrire complètement le comportement non linéaire jusqu'à la rupture ainsi qu'à déterminer la rigidité aux charges d'exploitation. Tous les résultats de cette recherche ont été vérifiés en les comparant à des données expérimentales. L'étude faite sur les assemblages simples à branches multiples est incomplète puisqu'il manque des données expérimentales.

ZUSAMMENFASSUNG
Die vorliegende Forschungsarbeit beschreibt eine breite Untersuchung des Verhaltens von T und DT Knotenpunktsverbindungen. Halb-analytische Formeln werden gegeben für Anfangssteifigkeit, Festigkeit unter einfacher und mehrfacher Belastung und für die Sekantensteifigkeit bei jeder Belastung bis zum Erreichen der Traglast. Diese Daten sind ausreichend, um das ganze nicht-lineare Verhalten bis zum Erreichen der Traglast darzustellen und um die Steifigkeit bei der vorhandenen Belastung zu bestimmen. Die gesamte Forschungsarbeit wurde verglichen mit experimentellen Daten aus einer grossen Datenbank. Die Arbeit an mehrfachen Knotenpunktsverbindungen ist nicht komplett weil experimentelle Daten fehlen.

1. INTRODUCTION

Tubular lattice girders and frames are popular in various building and offshore structures, so that tubular joints of various kinds are very common. The structural behaviour of such joints is complex, with each type of joint, its parametric variation of geometry and type of loading having considerable influence on the strength and stiffness characteristics.

This paper is restricted to T and DT (Double Tee) joints with loaded braces under single and combined (proportional) loading and as a special case, multibraced joints with loaded and unloaded braces (Fig. 1). Simple formulae have been established for the joint stiffness, strength and non-linear behaviour of these joints. Semi-analytical models are used as a basis, and a large experimental data bank used to assess the values from existing and proposed formulae.

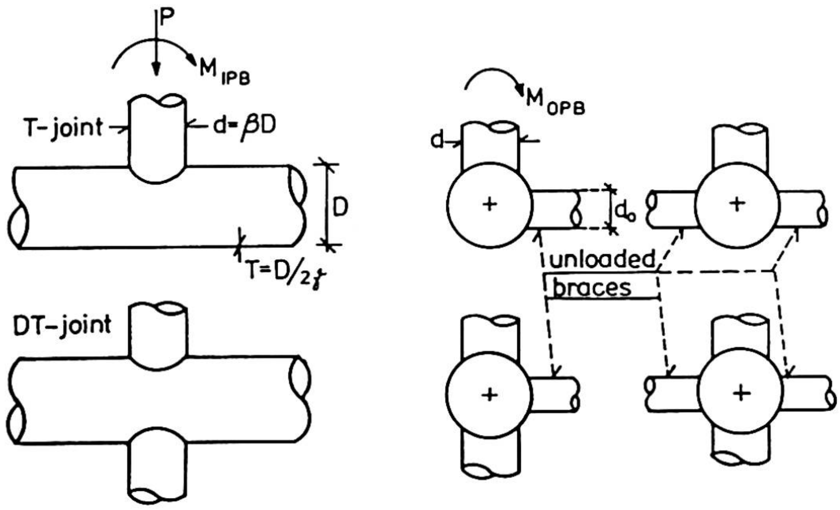


Fig. 1 Joint types investigated

2. ANALYTICAL MODELS FOR INITIAL JOINT STIFFNESS

2.1 T and DT joints

Empirical formulae are available for the initial joint stiffness (or flexibility) of T and Y joints only,[3,4,5], which gives stiffness values higher than those observed experimentally. Experimental studies using epoxy resin (Araldite) models, gives consistently higher stiffness values than those with steel models for all cases (see Figs. 2,3,4). This may be due to different material properties and effect of weld intersection.

The real complex behaviour of T and DT joints under axial and OPB moment loading of the brace can be approximated by using a simplified model where the three dimensional behaviour of the joint is represented by assuming a two dimensional ring (Fig. 2). The following derivation is made for the initial axial stiffness K_o :

$$K_o = P/\delta_o = \frac{(B_e/D)}{\gamma^3 f_o(\beta)} ED = k_o ED \tag{1}$$

where $f_o(\beta)$ is a complicated function of β and $\alpha = arcsin\beta$. This function $f_o(\beta)$ can be closely approximated by the function $(1-\beta)^s$ where the exponent "s" has an average value of 1.13. By assuming a power law dependence upon γ for B_e/D and then fitting all the available experimental data to equation (1), a formula (2) presented in Fig.2 can be found for K_o of T joints. Similarly, this procedure gives formula (3) shown in Fig. 3 for the initial OPB stiffness of T joints.

Fig. 2 gives a plot of all the initial axial stiffness data of T joints versus β. Formula (2) is expressed with lines of constant γ values of 8, 15 and 24, showing reasonable agreement with the data points. Test values on plastic (epoxy) tubes [4] are also shown in Fig. 2.

Fig. 3 gives a plot of all the initial OPB stiffness data of T joints and a formula (3) based on a similar procedure, along with the data points from tests on plastic tubes.

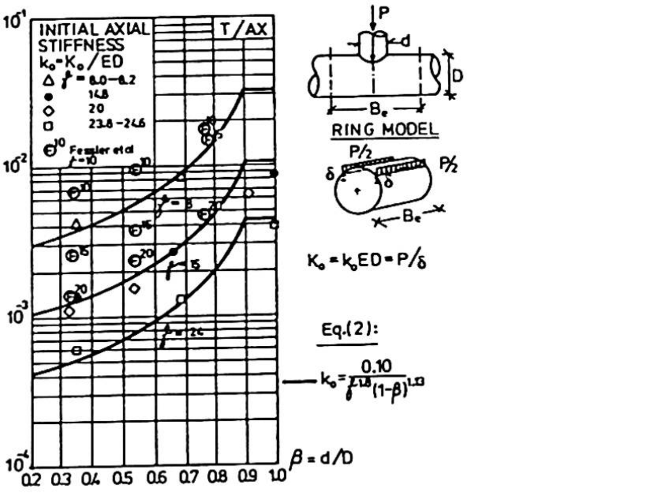


Fig. 2 Initial axial stiffness of T joints vs. β

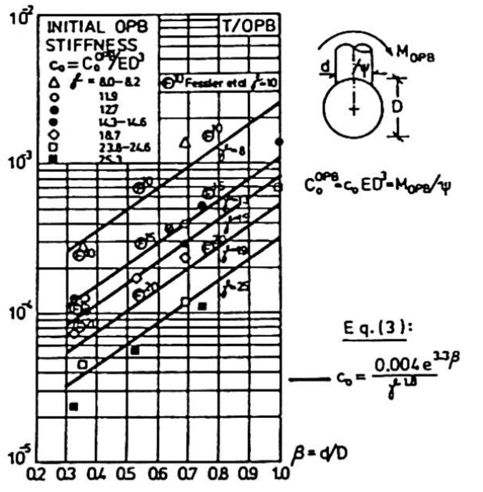


Fig. 3 Initial OPB stiffness of T joints vs. β

The analogy of a beam on elastic foundations (BEF) is applied for the initial IPB stiffness of T joints by assuming the section of the chord between brace saddle points as a beam over the entire chord length, supported by the remaining sector as a BEF along at the two longitudinal edges of the beam. On the basis of the expressions derived for the foundation stiffness (k_f) and bending stiffness of the beam (EI_b), a formula (4) shown in Fig. 4 is developed for the IPB stiffness of T joints. Fig. 4 shows all the relevant experimental data for the IPB stiffness of T joints (with formula (4)) plotted as lines of constant γ (10, 15, 25). Data points are also shown from the tests on plastic tubes [4]. Similar comparisons as above with the available experimental data and formulae based on the ring model and the analogy of a beam on elastic foundations are also developed for approximating the initial axial, OPB and IPB stiffness of DT joints [1].

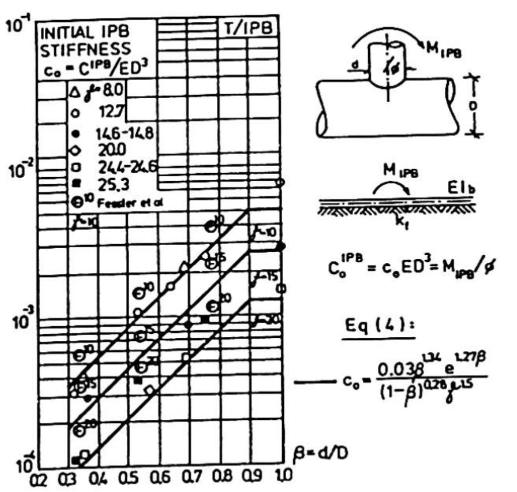


Fig.4 Initial IPB stiffness vs. β

2.2 Simple multibraced joints with unloaded braces

Formulae for the initial axial and OPB stiffness of simple multi-braced DT and T joints with unloaded braces in a perpendicular plane to loaded braces can be derived by applying the ring model where a rigid cap between the brace saddle points is assumed. Because of the enormous complexity of the cases with only one unloaded brace in the joint, only symmetrical cases of DT and T joints with two unloaded braces have been considered at present. Joint stiffness

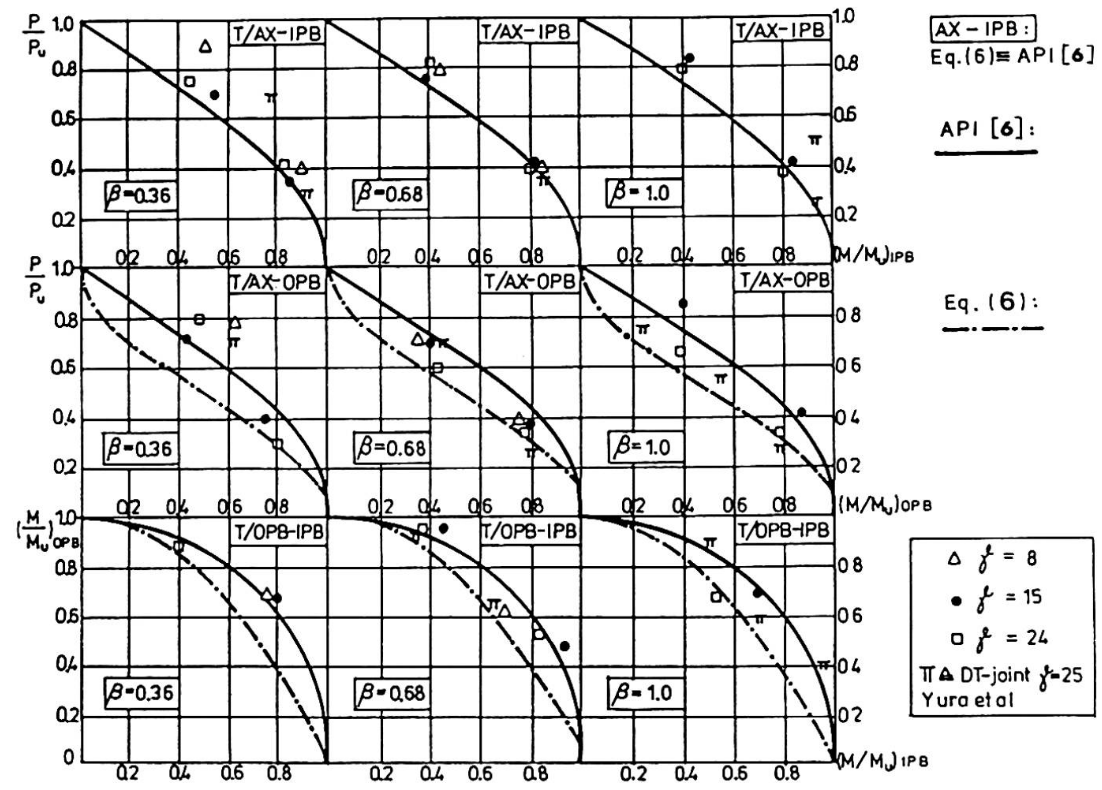


Fig. 5 Results of 2D interaction tests (AX-IPB,AX-OPB,IPB-OPB) for $\beta = 0.36, 0.68, 1.0$

equations derived on the basis of the above model cannot be further developed and calibrated because of the lack of experimental data. Experimental testing of these joints planned to be carried out in the near future will provide some reliable data points for finalizing the model.

3. JOINT STRENGTH MODELS UNDER SINGLE BRACE LOADS

A number of basic failure modes or their combinations are identified for DT and T joints under single brace loads [2] depending upon the joint parameters and loading conditions. Semi-analytical models such as ring models with plastic hinges [2,9] and the punching shear model [2] have been used. The present work extends this theory for axial load and OPB moment. For IPB moment a BEF analogy has also been used. Because of the complexity of the derived formula and the scatter (or lack) of experimental data, the calibration of the formulae have not yet been performed. This work has taken lower precedence because of recent international agreement [7] on comprehensive, simple design rules. However, an insight into the failure modes has been obtained.

The ultimate strength of simple multi-braced joints with unloaded braces is also studied on the same lines as above. In this case, however, no experimental data is available yet for calibrating the models.

4. JOINT STRENGTH UNDER COMBINED BRACE LOADS

In service the joints, especially in three dimensional tubular structures, are subjected to the combined action of axial and bending moment (IPB and OPB) loads in the brace. Only T and DT joints are considered. Ultimate brace loads due to interaction effects are further complicated due to the dependence upon the load vector and whether the loading is incremented proportionally or non-proportionally. Therefore, only empirical approaches have been used. Such a formula is [8]:

$$\frac{P}{P_u} + \left(\frac{M}{M_u}\right)_{IPB}^{2.1} + \left(\frac{M}{M_u}\right)_{OPB}^{1.2} = 1 \qquad (5)$$

The above formula does not fit the experimental results [10]. A semi-analytical interaction equation is suggested for T and DT joints, based upon a modification to the theoretical plastic strength of tubular section:

$$\frac{P}{P_u} + \frac{2}{\pi} arcsin \sqrt{\left(\frac{M}{M_u}\right)_{IPB}^{2} + \left(\frac{M}{M_u}\right)_{OPB}} = 1 \qquad (6)$$

The API rules [6] use the unmodified formula. Both the API rules [6] and equation (6) take the IPB-OPB coupling effect into account, which equation (5) does not.

An inspection of the 2 D interaction plots of all the available experimental data in Fig. 5 shows that the collapse mecanisms are different, with the API rules [6] unable to give safe lower bounds to the interaction data. A check is also carried out against 3 D interaction ($P - M_{IPB} - M_{OPB}$) by substituting test results [10] into equation (6). The results confirm that the generated yield surface is a reasonable lower bound also for 3D behaviour. This is also valid for 3D interaction tests on DT joints [11].

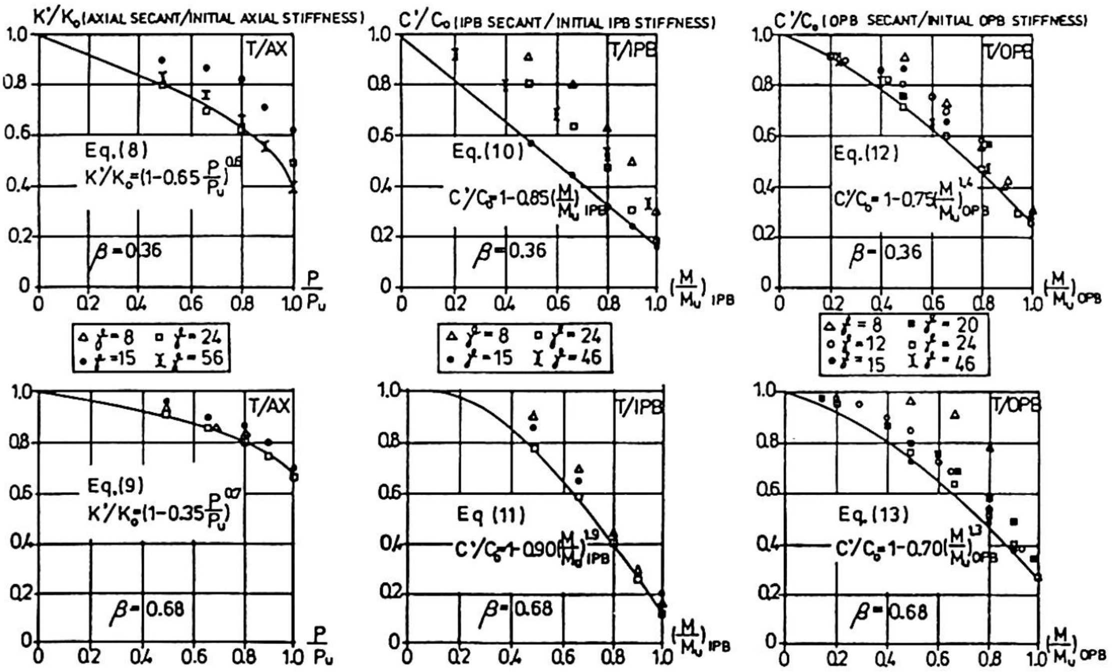


Fig. 6 Normalized axial, IPB and OPB secant stiffnesses of T joints for $\beta = 0.36$ and 0.68

5. NON-LINEAR JOINT BEHAVIOUR UNDER SINGLE BRACE LOADING

Normalized secant stiffness values at various normalized load levels (as a percentage of ultimate load) have been recorded from the experimentally obtained non-linear load-deflection plots in the data bank, as shown for T joints in Fig. 6. DT joints have also been treated similarly [1]. Lower bound equations such as shown in Fig. 6 have been deduced, based upon the lowest experimentally obtained secant stiffnesses. Once the initial stiffness (K_o, C_o) and the ultimate load (P_u, M_u) are known or calculated from formulae, the secant stiffness at various load levels can be determined from these equations to retrace the complete non-linear behaviour. If necessary, the tangent stiffness can also be determined from the equation or the non-linear plot using two close load levels. In this way, correct joint stiffnesses may be derived for any design criteria under working load levels.

6. CONCLUSIONS

Initial stiffness and strength formulae have been established or confirmed for T and DT joints under single brace loading. This will be done for simple multibraced joints when planned experimental work is completed. A lower bound interaction formula is also established for joint strength under combined loading for T and DT joints, which satisfies all experimental data. Finally, lower bound stiffness formulae for tracing the non-linear behaviour of T and DT joints up to ultimate load have been established. This can be useful in calculating the tangent or secant stiffness at any (working) load level in accordance with design criteria.

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