FURTHER RESEARCH ON CHORD LENGTH AND BOUNDARY CONDITIONS OF CHS T- AND X-JOINTS

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ABSTRACT: In the past many questions existed regarding the effect of the chord length and boundary conditions on the static strength of tubular joints. In addition to previous research by van der Vegte (1995), the current study focuses on the numerical analyses of axially loaded X-joints with the chord length parameter α, the brace-to-chord diameter ratio β, the chord thickness ratio 2γ and the chord end conditions (i.e. free versus fully restrained chord ends) being the major variables.

Based on finite element (FE) results, the effect of the chord length and the boundary conditions on the static strength of the X-joints considered is presented. The results are briefly compared with (i) van der Vegte's previous data (1995) on X-joints and (ii) the chord length effect found for CHS T-joints by van der Vegte and Makino (2006).

It is concluded that the influence of boundary conditions can be much more pronounced than originally anticipated. Hence, in designing test specimens or re-evaluating experiments conducted in the past, special attention should be given to these issues in order to prevent the chord length and boundary conditions having a significant influence on the results.

Keywords: Tubular joint; circular hollow section; T-joint; X-joint; finite element analysis; chord length; boundary conditions

1. INTRODUCTION

At present, design equations for tubular joints are primarily based on isolated joint data either obtained from experiments or numerical analyses. As joints are part of an overall structure, the load transfer through the joint may be different from that in isolated joints, depending on the boundary conditions employed. In the past, many questions existed regarding the effect of the chord length and boundary conditions on the strength of tubular joints. However, with the availability of numerical methods to generate reliable data, in the last two decades, multiple numerical studies were conducted to investigate the influence of boundary conditions and chord length on the strength of tubular joints.

Various researchers assessed the effects of boundary conditions on the strength of uniplanar K-joints by comparing isolated joint versus frame behaviour. In general, the conclusion was that the influence of restraints could be significant (e.g. Connelly and Zettlemoyer [1], Bolt et al. [2], Choo et al. [3]).

For uniplanar T-joints, the evaluation of the chord length and boundary conditions is not as straightforward as for K- or X-joints due to the interaction between brace load and in-plane bending chord moments. In addition, for uniplanar T-joints, chord end plates are necessary to react the brace load, making a simple comparison between the behaviour of unrestrained and restrained chord ends impossible. Van der Vegte and Makino [4] excluded the effect of in-plane bending moments and chord length by applying compensating in-plane bending moments to the chord ends. By adopting this approach, the effect of the boundary conditions on the strength of uniplanar T-joints could be made clear.

In 1995, van der Vegte analysed the effect of the chord and can length on the strength of X-joints under axial brace load for a limited range of non-dimensional geometric parameters, using the FE package MARC [5]. Although the brace-to-chord diameter ratio β (= d_1/d_0) covered a wide range of 0.25 - 1.0, the chord length parameter α (= $2l_0/d_0$) was varied between 3 and 18 for a single value of the chord thickness ratio 2γ (d_0/t_0 = 25.4), whereby the chord ends of the joints were unrestrained. It was concluded that for the geometric parameters investigated, a value of $\alpha > 12$ would have minor effect on the strength of the X-joints.

However, because recent research results briefly presented in section 3.2, revealed that the effect of the chord length and boundary conditions could be significantly more pronounced for 2γ values greater than 25.4, further research was carried out, presented in this publication.

Numerical analyses are conducted on sixteen X-joint configurations subjected to axial brace compression, considering four β and four 2γ ratios. Unlike T-joints where end plates are required at the chord ends to support the joint, for X-joints, the chord ends can be either free or restrained. Section 3.2 describes two alternatives for restraining the chord end and the effect each concept has on the ultimate capacity of the joint. The X-joints considered in the parametric study are analysed for both free and restrained (i.e. covered by rigid end plates) chord ends. Section 4 evaluates the effect of chord length and boundary conditions on the static strength of the CHS-to-CHS X-joints investigated.

More recently, Voth and Packer [6] conducted a parametric numerical investigation into the effect of chord length and boundary conditions of branch plate-to-CHS joints, similar to the present study on CHS-to-CHS X-joints. The joints analysed by Voth and Packer [6] covered transverse plates welded to both sides of the chord (i.e. X-type joints). Nine geometric configurations, consisting of three values of β (0.2 - 1.0) and three values of 2γ (19.7 - 45.8) were analysed for five values of the chord length parameter α (8 - 24). The end conditions of the chord were either free or fully restrained. All joints were subjected to branch plate tension load. In section 4, the findings of Voth and Packer [6] on branch-plate-to-CHS joints are compared with the observations made for CHS-to-CHS X-joints.

Based on the FE results, recommendations are made with respect to the chord length to be used in experimental programmes. Furthermore, selected results of the current study are compared with numerical data obtained from van der Vegte's previous study on X-joints [7]. Finally, a brief comparison is made with the chord length effect found for CHS T-joints by van der Vegte and Makino [4].

2. RESEARCH PROGRAMME

The configuration of uniplanar CHS X-joints and the definition of the geometric parameters are illustrated in Figure 1. Table 1 lists the geometric parameters and dimensions of the X-joints investigated. The chord diameter d_0 is 406.4 mm for all joints. Four values of β (0.25 - 0.98) and four 2γ ratios (25.4 - 63.5) are considered. For the joints with β = 0.25 and 0.48, the brace-to-chord thickness ratio τ (= t_1/t_0) is taken as 0.5, while for the joints with β = 0.73 and 0.98, τ is set to 1.0. Each of the joints is analysed for the following five values of the chord length parameter α: 12, 16, 20, 24 and 28, for both free and restrained (i.e. covered by rigid end plates) chord ends.

The steel type used for all members is S355 with a yield strength f_y = 355 N/mm^2 and an ultimate tensile strength f_u = 510 N/mm^2.

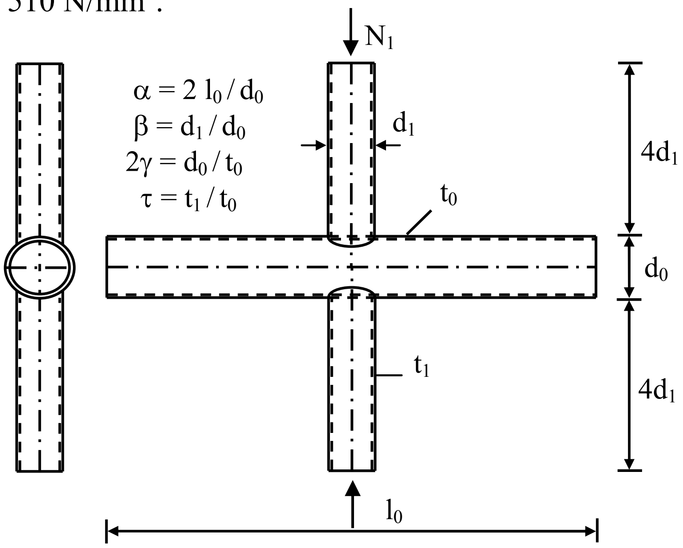


Figure 1. Configuration of a CHS X-Joint

Table 1. Geometric Parameters and Dimensions Investigated

d_0 = 406.4 mm		β			
		0.25 (d_1 = 101.6 mm)	0.48 (d_1 = 193.7 mm)	0.73 (d_1 = 298.5 mm)	0.98 (d_1 = 398.3 mm)
2γ	25.4 (t_0 = 16.0 mm)	τ = 0.5 (t_1 = 8.0 mm)	τ = 0.5 (t_1 = 8.0 mm)	τ = 1.0 (t_1 = 16.0 mm)	τ = 1.0 (t_1 = 16.0 mm)
	36.9 (t_0 = 11.0 mm)	τ = 0.5 (t_1 = 5.6 mm)	τ = 0.5 (t_1 = 5.4 mm)	τ = 1.0 (t_1 = 11.0 mm)	τ = 1.0 (t_1 = 11.0 mm)
	50.8 (t_0 = 8.0 mm)	τ = 0.5 (t_1 = 4.0 mm)	τ = 0.5 (t_1 = 4.0 mm)	τ = 1.0 (t_1 = 8.0 mm)	τ = 1.0 (t_1 = 8.0 mm)
	63.5 (t_0 = 6.4 mm)	τ = 0.5 (t_1 = 3.2 mm)	τ = 0.5 (t_1 = 3.2 mm)	τ = 1.0 (t_1 = 6.4 mm)	τ = 1.0 (t_1 = 6.4 mm)

Notes:
- each X-joint is analysed for α = 12 (l_0 = 2438.4 mm), α = 16 (l_0 = 3251.2 mm), α = 20 (l_0 = 4064.0 mm), α = 24 (l_0 = 4876.8 mm) and α = 28 (l_0 = 5689.6 mm)
- each X-joint is analysed for both free as well as rigid chord ends

3. NUMERICAL MODELLING

3.1 General

The current numerical analyses are carried out with the FE package ABAQUS/Standard [9], while the numerical analyses in van der Vegte's research [7] used the FE programme MARC [5]. The FE models generated in both studies are similar and can be summarized as follows.

Due to symmetry in geometry and loading, only one eighth of each X-joint is modelled, whereby the appropriate boundary conditions are applied to the nodes in the various planes of symmetry. The joints are modelled with eight-noded (quadratic) thick shell elements employing reduced integration (ABAQUS element S8R). Seven integration points through the shell thickness are applied. Figure 2 illustrates the FE mesh generated for the joints with $\beta = 0.48$.

For all joints except $\beta = 0.98$, the geometry of the welds at the brace-chord intersection is modelled using shell elements. Experimental and numerical research on axially loaded uniplanar and multiplanar X-joints (van der Vegte et al. [8]) revealed that the use of shell elements to simulate the welds provides accurate predictions of the load-displacement response of the X-joints considered. The dimensions of the welds adopted in the numerical model are in accordance with the specifications recommended by the AWS [10].

Axial brace loads are applied using the displacement control method i.e. prescribing the vertical displacement of the nodes of the brace tip.

Since the incorporation of material- and geometric non-linearity in ABAQUS and MARC requires the use of true stress-true strain relationships, the engineering stress-strain curve is modelled as a multi-linear relationship and subsequently converted into a true stress-true strain relationship. The hardening rule proposed by Ramberg-Osgood is used to describe the true stress-true strain behaviour. Both the engineering stress-strain curve and the true stress-true strain relationship of S355 (the steel grade used in this study) are shown in Figure 3.

Van der Vegte et al. [8] concluded that if plastification of the chord cross section is the major failure mode, the FE models as described above may provide accurate simulations of the static behaviour of T- and X-joints under axial brace loading.

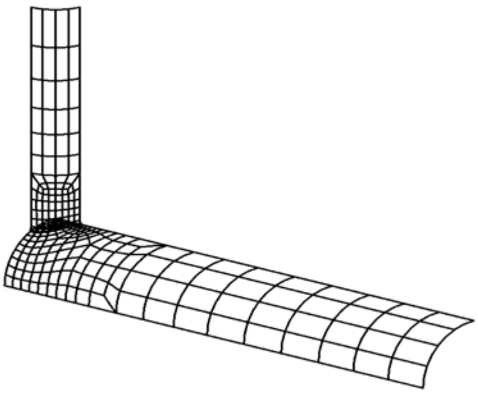


Figure 2. FE Mesh Generated for the X-Joints with $\alpha = 16$ and $\beta = 0.48$

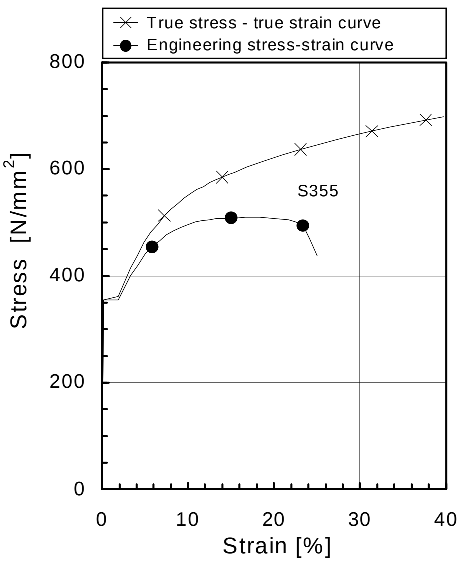
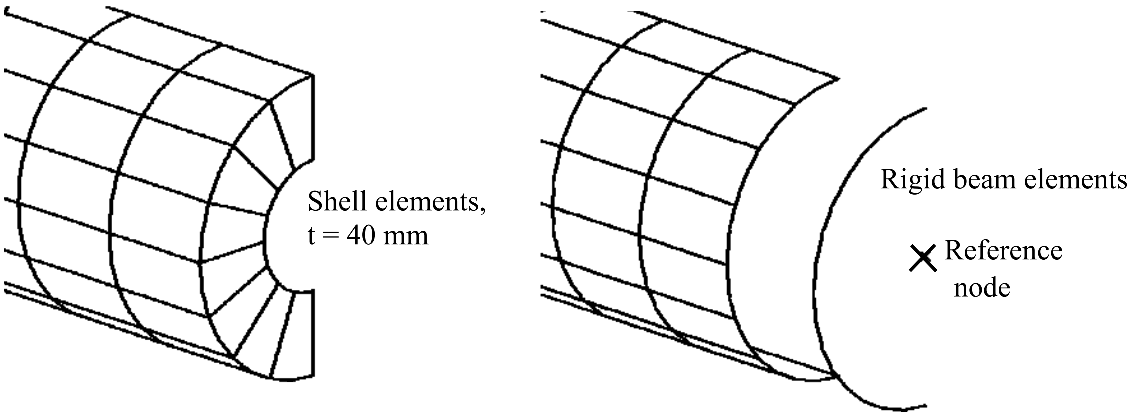


Figure 3. Engineering and True Stress - True Strain Curves for S355

3.2 Boundary Conditions

Unlike uniplanar X-joints for which no chord end plates are required, for uniplanar T-joints, end plates are necessary to support the joint. In preliminary FE analyses conducted on uniplanar T-joints with the chord thickness ratio 2γ varying from 14.5 to 50.8, the chord ends were covered by 40 mm thick steel plates, shown in Figure 4a. The material properties of the end plates were equal to those of the tubular members (S355). Although these end plates are very stiff in-plane, out-of-plane deformations are still possible.



(a) Deformable End Plates (b) Rigid Beams (Last Row of Chord Elements not Shown)

Figure 4. Chord End Restraints

An alternative method is shown in Figure 4b. Rigid beams are attached to the chord end, whereby boundary conditions are applied to the reference node, located in the centre of the chord cross section. Because of the rigid behaviour of the beams, the chord end cross section can not deform, but is able to translate and rotate.

From the preliminary analyses, it was found that for the thick walled joints with $2\gamma = 14.5$, the effect of the boundary conditions is almost negligible. However, for the thin walled T-joint with $2\gamma = 50.8$ and $\alpha = 12$, the rigid boundary conditions increase the ultimate capacity up to 10% compared to the strength of the T-joint with deformable end-plates. The lower capacity obtained for the T-joint with the 40 mm thick end plates is primarily caused by the ability of the end plate to deform out-of-plane. For T-joints with rigid chord ends, the out-of-plane deformations of the chord end plate are prevented, enhancing the ultimate strength. Additional FE analyses on the joint with deformable end plates revealed that a further increase of the thickness of the end plates ultimately gives the same capacity as the values found for the T-joints modelled with the rigid beams.

Because the effect of chord end conditions is more pronounced than anticipated, it was recommended to further evaluate the effect of the chord end conditions of axially loaded X-joins, either modelled with or without rigid beams at the chord end.

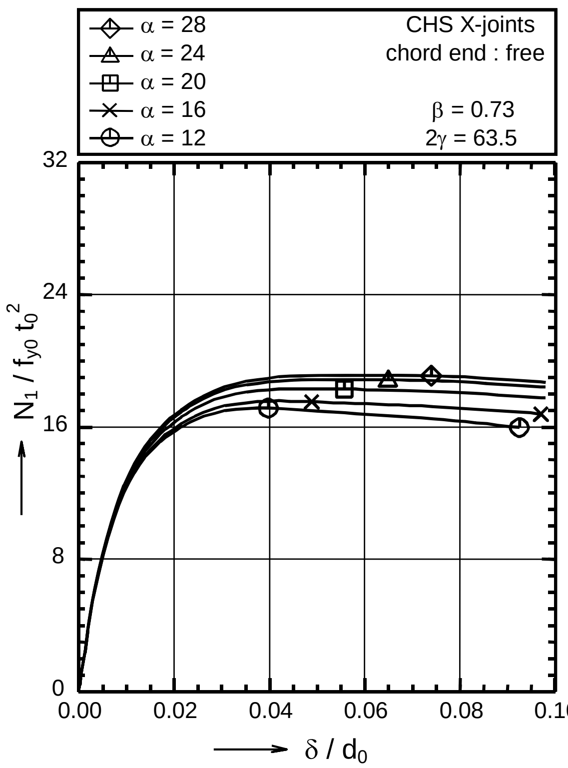
4. RESULTS AND OBSERVATIONS

4.1 Current Research

For each X-joint under axial brace load listed in Table 1, a load-indentation curve is derived, where indentation is defined as the vertical displacement of the crown point. As an example, Figure 5 illustrates the load-indentation curves obtained for the X-joints with $\beta = 0.73$ and $2\gamma = 63.5$ for both free and rigid chord ends. (Note that the symbols shown are only used to differentiate the various curves and do not refer to the failure loads.) The vertical axis displays the non-dimensional compression brace load $N_1/(f_{y0}t_0^2)$, where f_{y0} is the yield strength of the chord material and t_0 is the chord wall thickness, while the horizontal axis plots the non-dimensional indentation δ/d_0 of the crown point, where d_0 is the chord diameter. Ultimate load is defined as the brace load corresponding to the peak in the load-indentation curve.

Examination of both the load-indentation curves and the deformed shapes obtained from the FE analyses made clear that severe deformation of the chord wall i.e. chord plastification of the chord cross section at the intersection between the braces and the chord is the governing failure mode for the X-joints investigated. For the joints with $\beta = 0.25$, the deformations are located in the chord wall in the vicinity of the brace, while for the joints with $\beta = 0.98$ pronounced deformations are observed in the chord wall between the two braces.

Figure 6 plots, for all X-joints listed in Table 1, the (non-dimensional) ultimate load $N_{1,u}/(f_{y0}t_0^2)$ as a function of the chord length parameter α for both sets of boundary conditions. Open symbols in the diagrams refer to the unrestrained chord ends, whereas the filled symbols display the results of the X-joints modelled with rigid beams at the chord end.



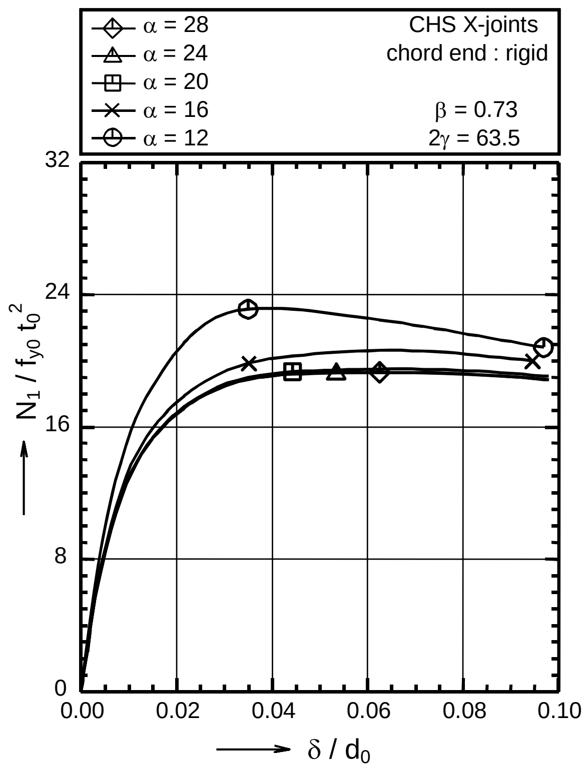


Figure 5. Load-Indentation Curves (in Non-Dimensional Form)
for X-Joints with $\beta = 0.73$ and $2\gamma = 63.5$

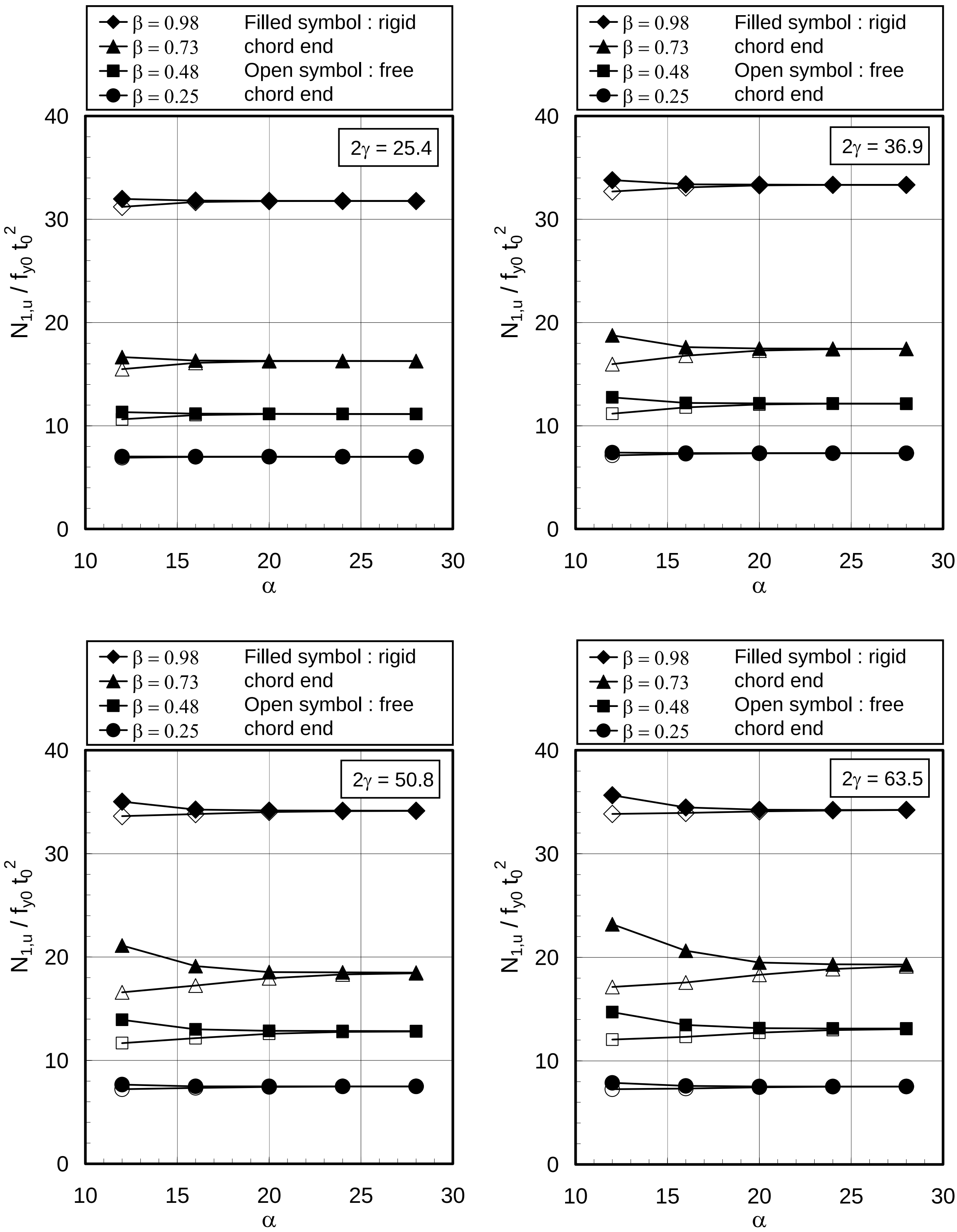


Figure 6. Non-Dimensional Ultimate Load $N_{1,u}/(f_{y0}t_0^2)$ as a Function of α

Figure 6 reveals that the chord length has a marginal or no effect on the ultimate strength for α values equal to or greater than 20. For these α values, the chord is sufficiently long to exclude possible chord end effects. As a result, the ultimate strength found for X-joints with $\alpha \geq 20$ is independent of the boundary conditions i.e. the presence or absence of chord end plates. This observation corresponds well with the research conducted by Voth and Packer [6] on plate-to-CHS X-joints under tension load.

For α values less than 20, the effect of α and boundary conditions directly depends on the values of β and 2γ. For the four 2γ values considered, the value of α hardly affects the strength of the X-joints with $\beta = 0.25$, even for the thin walled joints with $2\gamma = 63.5$. For $\beta = 0.25$, the deformation of the chord wall is limited to the area of the brace-chord intersection, preventing pronounced chord ovalisation to occur.

For the range of α values investigated, the chord length is also observed to have little effect on the ultimate strength of the joints with $2\gamma = 25.4$, in line with the observations made by van der Vegte [7] and Voth and Packer [6]. Chord ovalisation of thick walled joints dampens out quickly along the chord length, reducing the chord length participating in the joint behaviour.

On the other hand, for X-joints with relatively short chords ($\alpha \leq 16$) in combination with β values exceeding 0.25 or 2γ values greater than 25.4, the influence of the chord length and boundary conditions becomes significant. Using the strength for $\alpha = 20$ as reference strength, it is found that for X-joints with rigid chord ends, the strength enhances for chord lengths smaller than $10d_0$, whereas for the joints with free chord ends, the ultimate strength reduces if the chord length becomes smaller than $10d_0$. From Figure 6, it becomes clear that this effect is most pronounced for the intermediate β values (0.48 - 0.73) in combination with the largest 2γ values (i.e. thin walled joints).

The dependency of β can be explained by considering the effective chord length for uniplanar X-joints i.e. the section of the chord that is engaged in the load transfer from one brace to the opposing brace. For small β values, the deformation of the chord wall caused by the brace load is very localized, preventing pronounced chord ovalisation to occur. For intermediate β values, the chord section participating in the load transfer is considerably larger than for small β values, but reduces again for large β ratios. The influence of the chord length and boundary conditions on the joint strength follows the same pattern.

To explain the interaction between the chord length effect and the 2γ ratio, chord ovalisation should be taken into account. For increasing 2γ values, chord ovalisation dampens out slower along the chord length as compared to lower 2γ values. In other words, for thin walled joints the disturbance of the indentation at the brace-chord intersection covers a larger section of the chord than that for thick walled joints. Hence, the influence of the chord length and boundary conditions is most pronounced for thin walled joints. Voth and Packer [6] came to a similar observation.

For the X-joints considered, the largest effect of chord length and boundary conditions is obtained for $\beta = 0.73$ and $2\gamma = 63.5$. Using the strength of the X-joint with $\alpha = 28$ as reference, a strength enhancement of 20.1 % is found for the corresponding X-joint with rigid chord ends and $\alpha = 12$, whereas a strength reduction of 10.5 % is obtained for the same joint with free chord ends.

4.2 Comparison with Previous Data on X-Joints (van der Vegte [7])

Figure 7 shows the comparison between selected FE data (with $2\gamma = 25.4$) obtained in the current study and the results for $2\gamma = 25.4$ derived from a similar study by van der Vegte [7]. Both sets of data cover analyses on axially loaded X-joints without chord end plates. It is observed that for the joints with $0.25 \leq \beta \leq 0.73$, van der Vegte's FE data [7] for $11.5 \leq \gamma \leq 18$ match well with the current research results for $12 \leq \alpha \leq 20$ i.e. the chord length has little effect on the ultimate strength of these relatively thick walled joints. Van der Vegte's data [7] further show that for $2\gamma = 25.4$, a steep drop of the joint strength is only found for small α values ($\alpha < 8$).

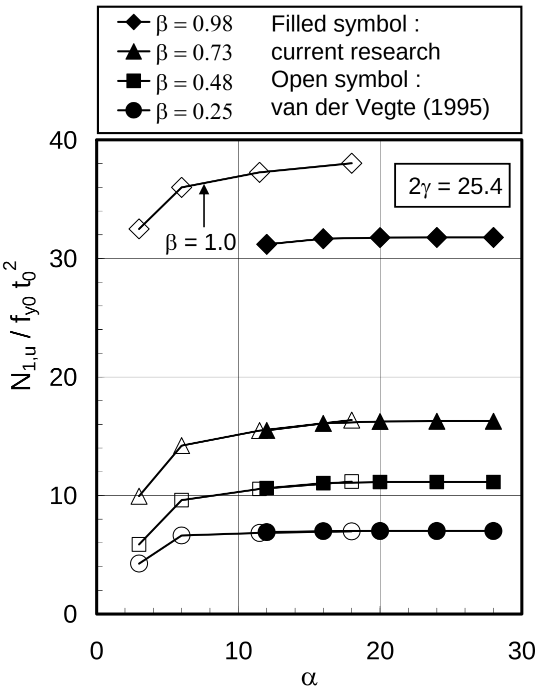


Figure 7. Current Research Results and van der Vegte's Data [7] for X-Joints ($2\gamma = 25.4$)

It should be pointed out that the strength of X-joints under axial brace load is rather sensitive with respect to β for joints with large β ratios ($\beta > 0.95$). As shown in Figure 7, a slight decrease of β (from $\beta = 1.0$ to 0.98) causes a significant reduction of the ultimate strength. In addition, the deformation capacity of X-joints with $\beta = 1.0$ is extremely small. Hence, research on X-joints with $\beta = 1.0$ was replaced by numerical analyses in the current study on joints with a slightly lower β value ($\beta = 0.98$). Nevertheless, Figure 7 shows that for both $\beta = 0.98$ and 1.0, the influence of the chord length parameter α is well in line with the trend found for the other β values.

4.3 Comparison with Research on T-Joints

In the numerical research carried out by van der Vegte and Makino [4] on uniplanar T-joints under axial brace, the same matrix of geometric parameters α, β and 2γ as shown in Table 1 was analysed. Because of the necessity for uniplanar T-joints to model chord end plates to react the brace load, a straightforward comparison between the ultimate strength of T-joints modelled with or without chord end plates is impossible. In addition, for T-joints, axial brace load unavoidably leads to chord in-plane bending moments affecting the joint strength. However, the approach of applying compensating moments to the chord end provides ultimate strength values independent of in-plane bending chord moments.

Figure 8 plots the strength of selected T-joints with compensating chord end moments ($2\gamma = 25.4$ and 63.5) as a function of α. A comparison between the results shown in Figure 8 and data for corresponding X-joints with rigid chord ends reveals that the observations regarding the effect of chord length and boundary conditions are similar for both types of joints: (i) the chord length has little effect on the ultimate strength of the joints with $2\gamma = 25.4$ or $\beta = 0.25$ and (ii) for joints with rather short chords ($\alpha \leq 16$) in combination with β values exceeding 0.25 or 2γ values greater than 25.4, a strength enhancement is observed for decreasing values of the chord length.

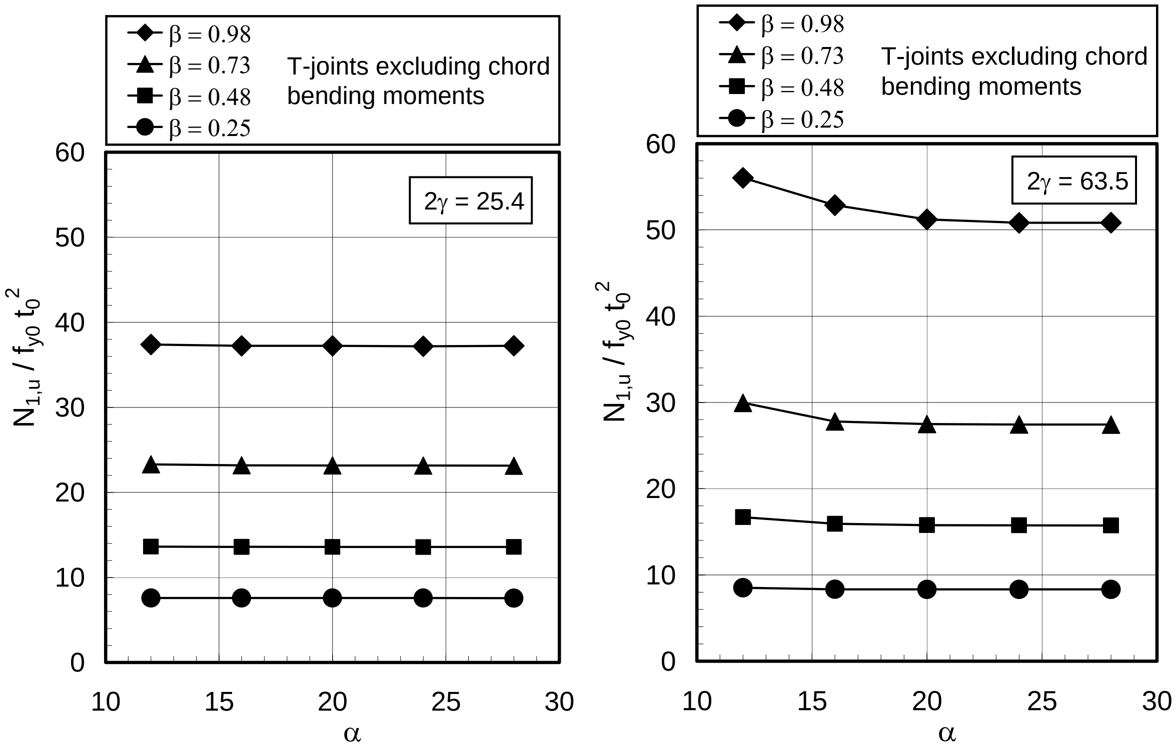


Figure 8. Van der Vegte and Makino's Data [4] for CHS T-Joints

4.4 Experimental Results

It should be noted that in various test series carried out in the past, no information is presented regarding the chord length or boundary conditions. However, even for the references that provide these details, α values equal to 12 or even less are not uncommon. As indicated by the presented research, these test results could be significantly affected by the chord length or boundary conditions.

The experiments conducted by Scola et al. [11] on CHS T-joints under axial brace load may serve as an example of (short) chord lengths that were applied in tests. After comparing Scola's results with experimental evidence and numerical data of various researchers, it was observed that Scola's test results are considerably higher for all β values considered (van der Vegte et al. [12]). Since the test specimens are reported to have a chord length parameter $\alpha = 4.8$, this discrepancy is likely caused by the short chords used in Scola's tests. A chord length parameter of $\alpha = 4.8$ in combination with 2γ values ranging from 26.8 to 44.5 is too short to exclude the effect of the chord end plates on the strength of axially loaded T-joints.

A similar conclusion can be drawn from the work of Voth and Packer [6]) on X-type branch plate-to-CHS joints. Very short chord lengths of $2d_0$ (for $2\gamma = 45.8$ and $\beta = 0.6$) were investigated to compare with the results of experiments that closely matched this geometry and length. From the numerical analysis, it became clear that the semi-rigid boundary conditions applied in the experiments likely increased the ultimate connection capacity by a considerable margin.

5. SUMMARY AND CONCLUSIONS

Numerical analyses are conducted on uniplanar CHS X-joints subjected to axial brace load for a wide range of the geometric parameters α, β and 2γ. In addition, the effect of the presence or absence of rigid end plates attached to the chord end is evaluated. Based on the presented research, the following conclusions can be drawn :

- Depending on the geometric parameters β and 2γ, both the chord length and the chord end conditions may have a significant influence on the ultimate capacity of X-joints. To exclude possible effects of the chord length and chord end conditions, a chord length of at least $10d_0$ ($\alpha \geq 20$) is recommended, while for X-joints with $2\gamma \leq 25$, a chord length of at least $6d_0$ ($\alpha \geq 12$) is sufficient to exclude the influence of the chord length on the ultimate strength.

- Although the effect of boundary conditions on the ultimate strength is more “hidden” for T-joints as compared to X-joints, the influence of the chord end restraints on T-joints is similar as the behaviour found for X-joints with rigid chord ends.

- In case of relatively short, thin walled chords ($\alpha = 12$ and $2\gamma \geq 50$) covered by end plates, the end plates should be designed with sufficient thickness in order to prevent the plates from having effect on the ultimate capacity of the joints.

- Before adopting the results of tests carried out in the past, careful screening should be conducted as the results may be affected by the chord length or chord end conditions.

- The above mentioned conclusions match well with the results of FE research on X-type transverse plate-to-CHS joints under tensile loading conducted by Voth and Packer [6].

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