Tubular Structures X – Jaurrieta, Alonso & Chica (Eds.)
© 2003 Swets & Zeitlinger, Lisse, ISBN 90 5809 552 5

Study of the behaviour of welded joints composed of elliptical hollow sections

C. Pietrapertosa & J.-P. Jaspart
Department M&S, University of Liège, Liège, Belgium

ABSTRACT: Latest product of the hollow section family, the elliptical hollow section (EHS) from Arcelor Tubes allows the architects to realise light and transparent constructions. But its use requires the development of design and conception procedures for the welded connections between these profiles. Because of the recent arrival of the EHS on the market, design recommendations aren't available for this kind of connections. Nowadays these connections have to be checked by the experimental way, what is rather expensive. Therefore it is imperative to develop numerical models and analytical methods for the prediction of the resistance and ductility properties of elliptical hollow section joints. Moreover, present code recommendations for the calculation of tubular (circular and rectangular) connections are based on empirical formulations. But the current tendency for the connection design is to derive analytical formulae based on the so-called "component method" (Eurocodes 3 and 4). The purpose of this work is to investigate this topic. The resulting diploma work represents a first step in the development of connections between EHS profiles. It could therefore not be possible, in the framework of this diploma work, to derive the final analytical formulae for the calculation of elliptical connections. The objectives of this work which focuses on the behaviour of simple brace to chord joints were then the following: acquire a good knowledge of the physical behaviour of EHS connections, develop reliable numerical models to allow Arcelor to check easily some real cases and finally propose a background for an analytical formulation for the resistance of the joint.

1 INTRODUCTION

1.1 *The elliptical hollow section – an aesthetic choice.*

Result of a long collaboration with architects, elliptical and semi-elliptical hollow sections represent an attractive solution for all visible applications of steel structures. Indeed, elliptical hollow sections are used in a lot of prestigious projects such as the new terminal of Madrid Airport or the atrium "Coeur Défense" in Paris as shown in Figure 1.

1.2 *Structural and practical advantages*

The elliptical section, in addition to its aesthetic qualities, offers a good structural behaviour. This section has a striking advantage for use in structures exposed to wind as, because of its shape, it reduces considerably the loading. An example of this advantage is shown on Figure 2, which represents a tubular steel pole for "Electricité de France".

Its buckling behaviour is very interesting for members in compression. In addition to its excellent mechanical characteristics, the elliptical hollow section can be easily submitted to laser, flame or plasma-cutting. The centering (hot or cold) makes it possible to fulfill all architects' wishes and a hot galvanizing can be applied to insure the durability.

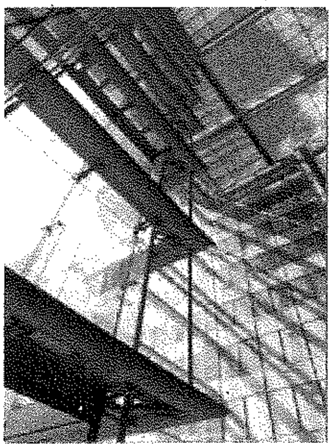

Figure 1. Atrium "Coeur Défense".

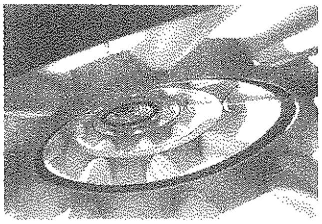

Figure 2. Tubular steel pole for EDF (M. Mimram).

1.3 *Design aspects*

The existing standards and calculation tables do not cover welded connections with elliptical elements. Eurocode 3 considers joints between open sections in appendix J while joints between rectangular or circular hollow sections are considered in appendix K. When the design of joints between elliptical hollow sections is to be approved by the authorities, it is therefore necessary to make verifications by experiment or numerical simulation. Therefore Arcelor, in collaboration with the University of Liège, decided to carry out fundamental investigations on welded joints with EHS in order to understand the behaviour of such connections and to start with the development of design analytical formulae.

1.4 *Description of the work*

This work on elliptical hollow section profiles includes several steps. First a study of the literature on design of CHS connections and RHS connections has been achieved. Tests on joints have been carried out and first conclusions on the joint behaviour have been drawn. Then, reliable numerical models have been developed and a parametric study has been carried out. Finally, existing analytical models for CHS have been adapted to EHS.

2 EXPERIMENTAL TESTS

Experimental tests are necessary to understand the physical behaviour of such joints. The aim of these tests was to observe the types of failure mode, the shape of the load-displacement curves and to pick out all the other information about the physical behaviour of the joints. On the other hand, the test results will be used as a reference to calibrate a FEM model (experimental curves P-Δ to be compared with numerical ones).

2.1 *Joint configuration and test set-up*

The specimens tested are joints (see Figure 3) subjected to compression and tension. The chord and the braces are made from elliptical sections and connected at 90 degrees. The specimens used for the tests are from two types. On the one hand, specimens with a 320×160, 8 mm thick chord. On the other hand, specimens with a more compact 220×11, 10 mm thick chord. Braces were identical in both cases: 120×60, 4 mm thick. The steel grade is S355 J2H for all profiles. Two specimens from each type were subjected to tension and one specimen was tested in compression. Tests were carried out with the help of a 100t press. Test-pieces were equipped with six displacement transducers and lime was used to observe the yield lines.

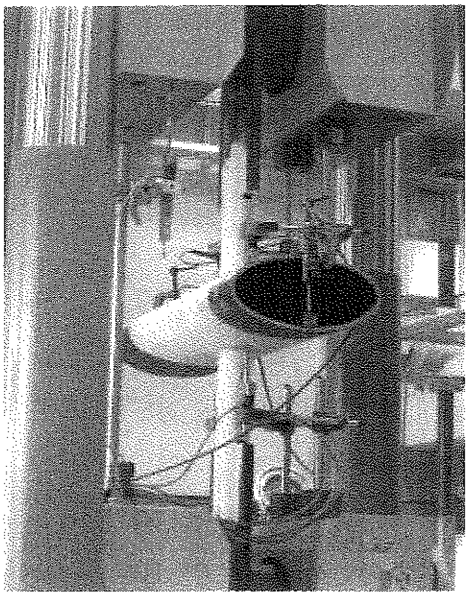

Figure 3. Specimen and test set up.

2.2 *Measurements*

All the geometrical dimensions of the specimens have been precisely measured. The shape of the cross-section appeared to be a perfect ellipse. The steel grade has also been checked and for the nominal steel grade S355, the actual yield limit appeared to be 480 N/mm^2.

2.3 *Results*

Important differences can be noted between tension and compression.

2.3.1 *Tension*

In the specimen subjected to tension, yield lines appear along the chord to form a mechanism (see Figure 4). However, on the P–Δ curves, there is no yield plateau for the load level corresponding to the mechanism. The rigidity decreases but remains good. This is due to

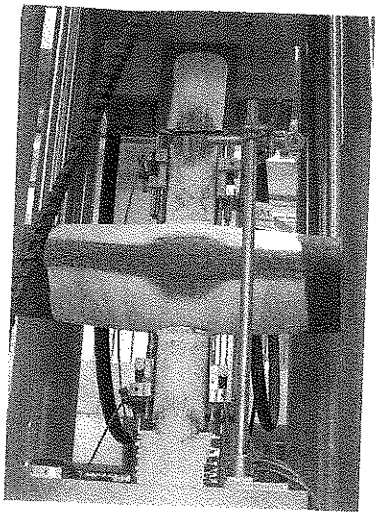

Figure 4. Specimen after tension test.

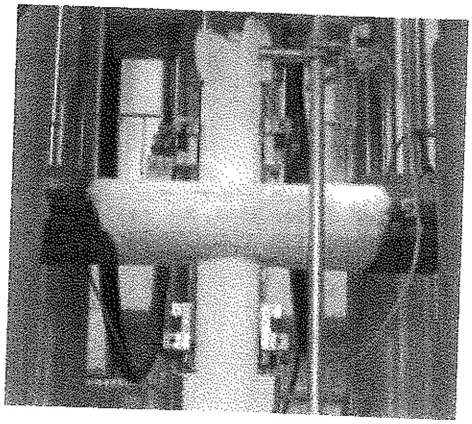

Figure 6. Specimen after compression test.

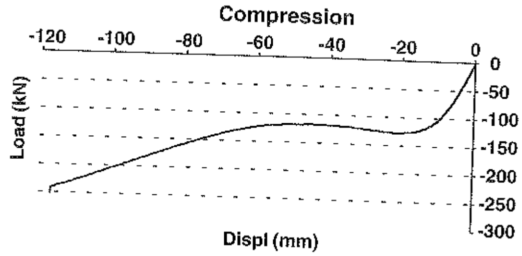

Figure 7. Experimental P–Δ curve in compression.

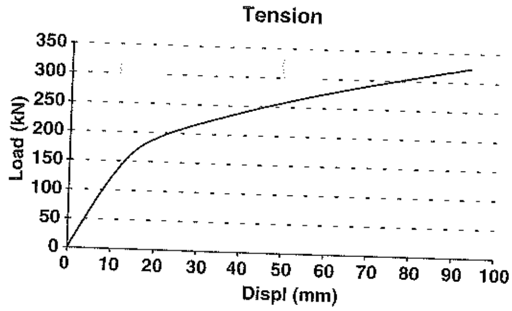

Figure 5. Experimental P–Δ curve in tension.

second order effects: because of the deformation of the chord, a membrane effect appears. Forces become parallel to the plan of the chord, membrane stresses develop and this effect increases the resistance of the joint. The development of the yield lines doesn't cause the failure of the joint. The joint has thus a great ductility (see Figure 5). The failure appears finally in the brace.

2.3.2 *Compression*

The compressi ehaviour exh a "Snap Trough" phenomenon, which is a local buckling of the shell. But this local buckling is preceded by a significant yielding of the brace due to the plastic punching of the brace in the chord (Figure 6). The test curve reaches a local maximum before dropping, which is the proof of an instability phenomenon (Figure 7). As for the tension case, a membrane effect then appears, which results in a further increase of rigidity (Figure 8). The good ductile behaviour of the joints has to be pointed out.

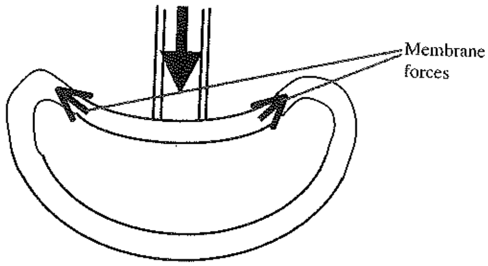

Figure 8. Membrane forces after buckling.

2.4 *Results*

The tests reveal important features. A comparison can be drawn between the two kinds of specimen tested. As well as in compression than in tension, the same behaviours and the same failure modes are observed. Obviously, the stockier specimen presents a higher initial stiffness and its capacity of deformation is much lower (Figures 9 and 10).

The most important considerations to keep from these tests are the different failure modes in tension and compression and the great deformation capacity

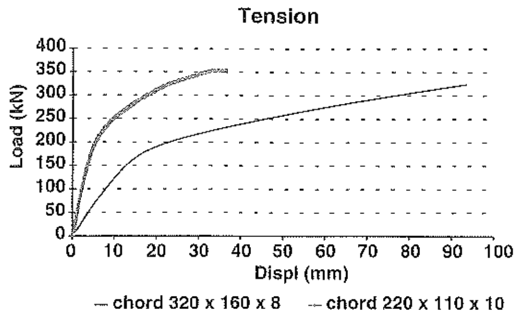

Figure 9. Comparison of the 2 types of specimen in tension.

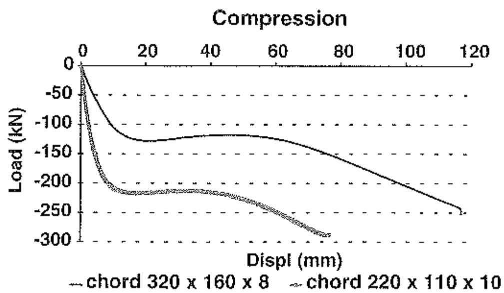

Figure 10. Comparison of the 2 types of specimen in compression.

of this kind of tubular connection thanks to second order effects (membrane stresses).

3 FEM SIMULATIONS

3.1 *Model calibration*

3.1.1 *Procedure*

On the basis of these experimental data, different numerical models have been calibrated. All the numerical simulations has been performed by means of the FEM software ABAQUS, with 4-nodes shell elements. The actual mechanical properties of the steel and geometry of the specimens have been introduced in the models. As the specimens tested present 3 plans of symmetry, only a eighth of the structure is represented (Figure 11). The welds have been modelled to take account of the high stiffness of the chord in this area. To achieve it, shell elements with higher young modulus, higher thickness and high yield limit have been used in order to prevent locally the chord from yielding (Figure 12).

3.1.2 *Comparison with test results*

For all the tests, the FEM simulations have been seen to be in perfect agreement with the experimental

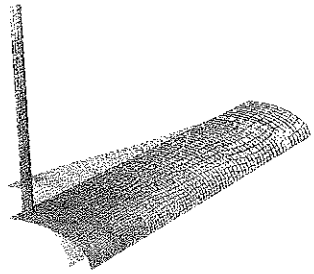

Figure 11. Numerical model of the joint and deformed shape.

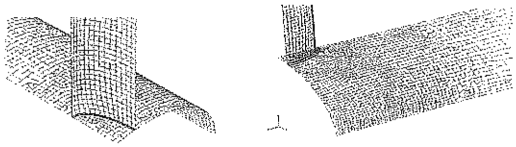

Figure 12. Modelling of the welds.

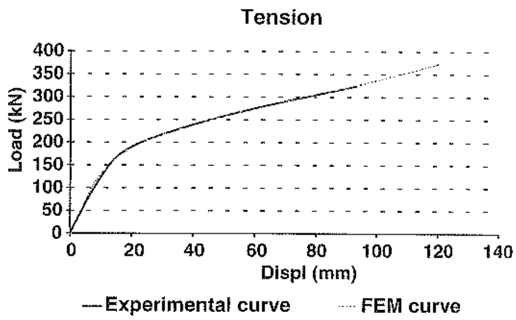

Figure 13. Comparison between experimental and numerical curves in tension.

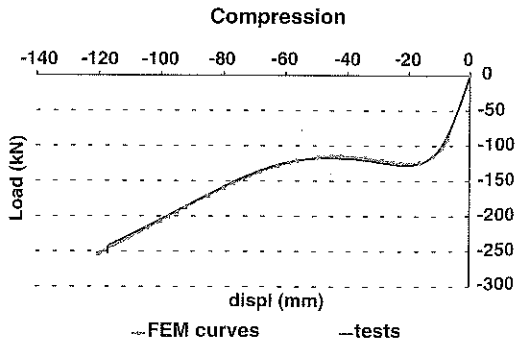

Figure 14. Comparison between experimental and numerical curves in compression.

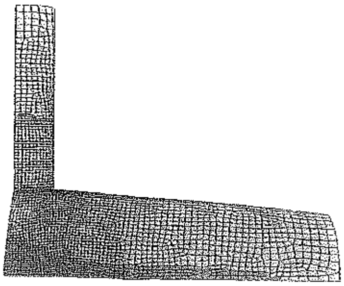

Figure 15. Yielding in tension.

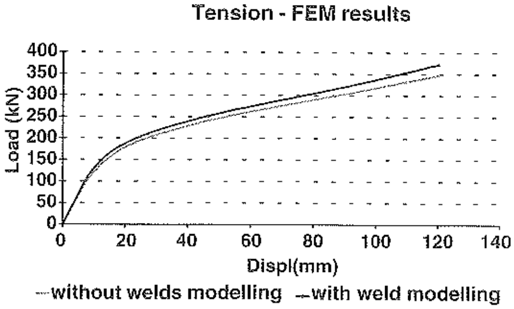

Figure 16. Welds influence.

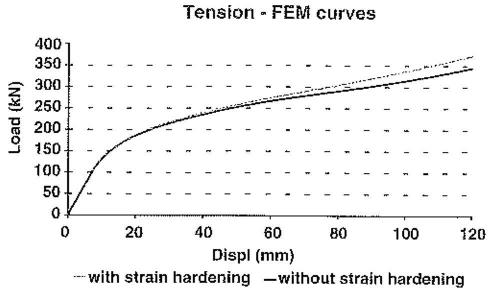

Figure 17. Steel strain hardening influence.

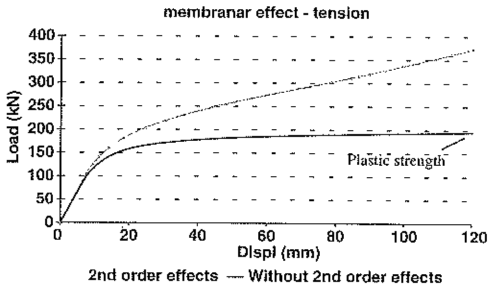

Figure 18. Membrane effect influence in tension.

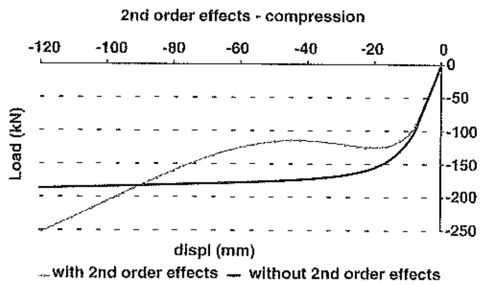

Figure 19. Influence of the second order effects in compression.

results. The FEM curves fit perfectly with the experimental ones, in compression and in tension (Figures 13 and 14). The difference is lower than 1%.

Similar failure modes have been found: yield lines for specimen in tension (Figure 15), punching and local buckling for those in compression. The FEM tool is thus considered as reliable and the study can be led further.

3.2 *Study of the behaviour*

The influence of several factors has been investigated. This study shows that welding and steel strain hardening have no significant effect on the behaviour of the joint (Figures 16 and 17).

On the other hand, it may be seen that the 2nd order effects have a major influence in tension. The membrane effects increase the resistance of the joint, in reference with the plastic resistance (Figure 18), and the instability in compression leads to the failure of the joint before the yield plastic strength is reached (Figures 18 and 19). These considerations about 2nd order effects are very important and they have to be taken into account in an analytical formulation.

The influence of the length of the chord has also been studied and it appears that the stiffness and the resistance increase with the length up to a maximum value called "influence length" (on Figure 20, it can be seen that the influence length for that joint is about 2400 mm).

This first numerical study reveals that the major factors influencing the behaviour of the joint are the length of the chord, and primarily, the second order effects.

3.3 *Parametrical study*

A parametrical study has then been carried out. A total of 64 simulations have been realised. The influence of several parameters has been studied: chord and brace thickness (t_0 and t_1), ratio between chord and brace diameter ($\beta = h_1/h_0$) and yield stress (f_y). Each simulation is performed in compression and in tension, with and without 2nd order effects. This parametrical study allowed pointing out other physical

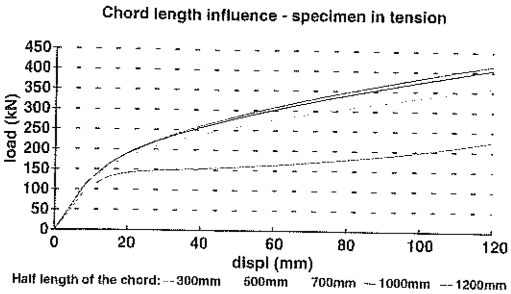

Figure 20. Chord length influence.

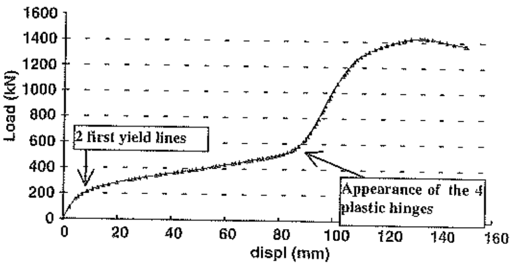

Figure 23. Illustration of the increase of stiffness due to membrane stresses.

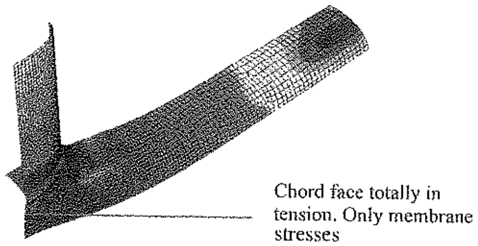

Figure 21. FEM model, shape of the chord after appearance of the whole plastic mechanism in the chord.

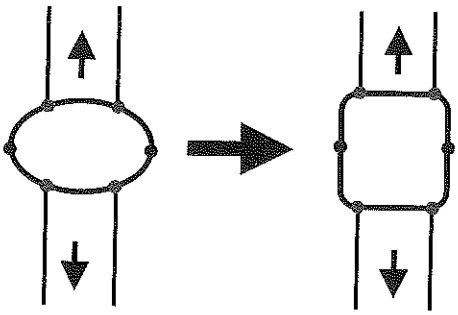

Figure 22. Complete plastic mechanism of the chord.

phenomena that can't be seen on the experimental tests. New failure modes appeared: for a low β ratio, failure by punching shear (failure by shear of the part of the chord around the brace), yielding of the brace in tension and buckling of the brace in compression with stocky chords. The models with a high β ratio revealed the whole plastic mechanism for the chord (Figure 21).

The experimental tests didn't allow reaching a whole mechanism because the brace failed before. So the complete plastic failure of the chord can now be explained: if a 2D model is considered (Figure 22), it can be seen that two first plastic hinges appears on both sides of the chord (yield lines observed in the experimental tests) and then for a higher load level, 4 plastic hinges appears at the bottom of the brace, forming the complete plastic mechanism. This 2D model is used later for an analytical model.

After the development of that mechanism, the chord faces are predominately in tension. On the P–Δ curve, the appearance to these hinges corresponds to a rise of the stiffness due to the action of the membrane forces (Figure 23).

4 ANALYTICAL FORMULATION

The final purpose of such a study is the formulation of design models to calculate the resistance of the joints. But it was not possible, in the framework of the diploma work, to propose a complete and full-calculated analytical procedure for the calculation of elliptical connections. As a first step of the present work, existing resistance models for CHS connections have been adapted to elliptical hollow sections.

Two approaches can be considered for the analytical procedure. In the first one, all types of failure and phenomena are included into a single plastic model based on the concept of effective width. In the second one, separate resistance formulae are chosen for each failure mode. This one is followed in the present study.

Different failure modes were observed in the experimental and numerical studies. Failure can occur in the chord by yielding, by buckling or by punching shear. As far as the brace is concerned, failure can occur by yielding or by buckling. For each failure mode, an analytical model has been adopted.

4.1 *Yielding of the chord*

The most frequent failure mode is related to the development of a plastic mechanism in the chord. The "Ring Model" (*J. Wardenier "Hollow Section Joints"*) has been adapted to elliptical chord cross-section. This model uses the plasticity theory and gives the plastic strength of the chord (without taking into account with the 2nd order effects).

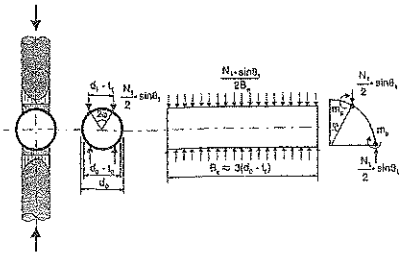

Figure 24. Ring model (Wardenier).

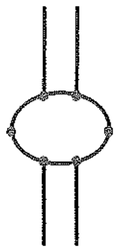

Figure 25. Plastic mechanism of the elliptical chord.

The plastic mechanism used to apply the ring model to the elliptical chord is shown on Figure 25. This is the mechanism met in the numerical study.

The ring model applied to that case gives the following expression for the plastic strength of an elliptical chord:

$$N_{pl} = \frac{2 f_{y0} B_e t_0^2}{(h_0 - t_0) - (b_1 - t_1)} \tag{1}$$

where B_e = the effective width of the chord; b = the great diameter of the elliptical section; h = the small one; t = the thickness. The suffix 0 relates to the chord and the suffix 1 to the brace. The effective width has to be evaluated by numerical or experimental ways.

4.2 *Punching shear*

Another type of possible failure mode is punching shear (crack initiation leading to pull out of the bracing from the chord – Figure .

The formula is simply the one prescribed for CHS but adapted to take account of the elliptical perimeter of the section (equation 2).

$$N_u = \frac{f_{y0} t_0 \pi \sqrt{\frac{1}{2}\left(h_1^2 + b_1^2\right)}}{\sqrt{3}} \tag{2}$$

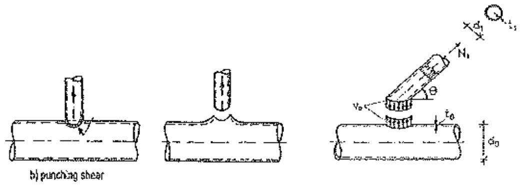

Figure 26. Punching shear for CHS.

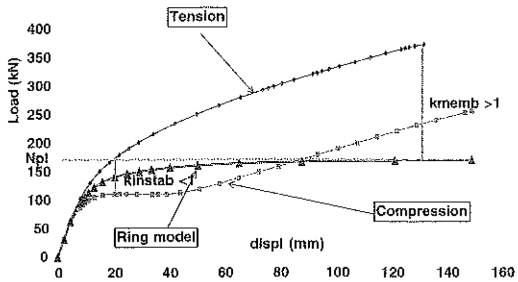

Figure 27. Illustration of the correction coefficients.

4.3 *Yielding of the brace*

Yielding of the brace is calculated on the basis of the elliptical section.

$$N_{pl} = t f_y \pi \frac{h_1 + b_1 - 2t}{2} \tag{3}$$

where b_1 = great diameter of the ellipse; h_1 = small diameter of the ellipse.

4.4 *Second order effects*

The ring model gives an estimation of the plastic strength of the chord. It has been observed during the experimental and numerical studies that 2nd order effects were significantly affecting this plastic strength. In tension, the plastic strength is increased by the membrane forces and in compression it is decreased because of a local buckling. The ring model has thus to be corrected with coefficients to take into account the second order effects. In tension the strength may be amplified, by a coefficient k_{memb} higher than one. In compression, a coefficient k_{inst} reducing the plastic strength is used (Figure 27).

The values for the effective length and the k coefficients have been determined by numerical simulations. Their analytical expression still needs to be developed.

5 CONCLUSIONS

In conclusion, the study of simple joints enables to better understand the behaviour of as regards to possible

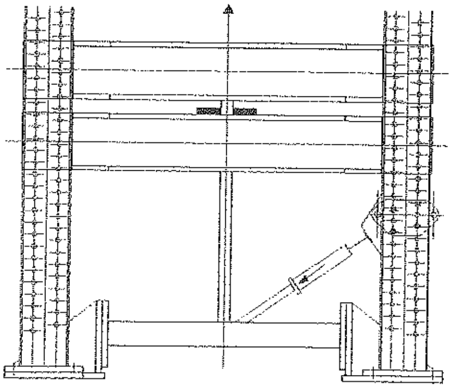

Figure 28. New tests on truss elements.

failure modes, resistance and ductility. Besides that, reliable numerical models are now available to check the strength and the ductility of such joints. Finally, this study forms the basis for analytical solutions, with strength models for different failure modes and different components. These models have still to be improved: the importance of the second order effects has to be quantified and the model for chord yielding has to be further worked out.

New tests will be carried out in order to study the behaviour of joints in trusses as shown on Figure 28.

Development of solutions for elliptical hollow sections nodes must be continued and extended to other types of joints, with focus of resistance, stiffness and ductility. When available, these formulations could then be introduced into calculation tables and standards, which would enable users to fully benefit from the possibilities of elliptical hollow sections.

REFERENCES

Pietrapertosa, C., 2002, Etude du comportement d'assemblages soudés de poutres en treillis constitués de profilés métalliques tubulaires de forme elliptique, Travail de fin d'études, Université de Liège.

Hibbit, Karlson, Sorensen, 2001, Abaqus/Standard User's manual, Pawtucket, U.S.A.

Jaspart, J., 1999, Semi-rigid Behaviour of Civil Engineering Structural Connections, Document COST C1, Université de Liège.

Wardenier, J., 1982, Hollow Section Joints, Delft University Press, Delft, The Netherlands.

de Winkel, G.D., 1998, The Static Strength of I-beam to Circular Hollow Section Column Connections, Delft University, ISBN 90-76554-01-3.

Eurocode 3, 1992, Design of steel structures. Part 1-1: General rules and rules for buildings, annexes J and K.

Wardenier, J., Kurobane, Y., Packer, J.A., Dutta, D., Yeomans, J.N., 1991, Assemblages de Sections Creuses Circulaires (CHS) sous Chargement Statique Prédominant », Comité International pour le Développement et l'Etude de la Construction Tubulaire, CIDECT.

Wardenier, J., Kurobane, Y., Packer, J.A., Dutta, D., Yeomans, J.N., 1991, Assemblages de Sections Creuses Rectangulaires (RHS) sous Chargement Statique Prédominant », Comité International pour le Développement et l'Etude de la Construction Tubulaire, CIDECT.

Bortolotti, E., Petitjean, P.D., 2002, Assemblages de tubes elliptiques, Usinor, rapport interne EBO2003R.