Testing and modelling of welded joints between elliptical hollow sections

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ABSTRACT: The elliptical hollow section, the most recent in the family of tubular elements, allows light and transparent design in steel structures. Welded connections between such elements are not covered by the existing standards and recommendations. When the authorities'approval is required for their design, experimental or numerical approaches have to be followed. This method was used to establish the load-bearing capacity of a joint included in a truss girder: an experimental test was successfully carried out on this connection and a computer model was calibrated. Furthermore, other simpler welded joints were tested in pure tension and compression and simulated numerically. In parallel with this work, theoretical investigations were initiated which should progressively lead to the development of analytical design formulae.

1 INTRODUCTION

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

Developed through a long partnership with architects, elliptical and semi-elliptical hollow sections represent a quite interesting solution for all visible applications in steel construction. Nowadays elliptical hollow sections are used in a lot of prestigious projects such as "Coeur Défense" or the new terminal of Madrid Airport as shown in figure 1.

Figure 1. New terminal of Madrid Airport (R.Rogers)

1.2 *Structural and practical advantages.*

In addition to its aesthetic qualities, the elliptical hollow section offers a good structural behaviour. Moreover this section has a striking advantage for structures exposed to wind, as it reduces the wind loading considerably (see, for instance, figure 2, which presents a tubular steel pole built for "Electricité de France").

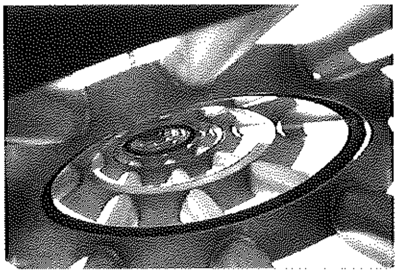

Figure 2. Tubular steel pole for EDF (M.Mimram)

As a hot-finished product, the elliptical hollow section offers superior resistance to buckling when used in compression. It can easily be further processed, either by cutting (laser, flame, plasma) or bending (hot or cold). It is also suitable for all surface treatments, such as hot-dip galvanizing, painting,...

1.3 *Assemblies including elliptical hollow sections.*

Welded connections between elliptical elements are not covered by the existing standards and design recommendations; and in particular by Eurocode 3 and its Annex K, which deal with the design of joints involving circular hollow sections. Therefore, in case the authorities'approval is required for the design of joints between elliptical hollow sections, an experimental or numerical approach must be followed.

This method was applied to estimate the strength of a joint in a truss girder. In parallel, more fundamental investigations were initiated, which aim at developing analytical design formulae.

2 CASE STUDY

2.1 *General view*

Elliptical hollow section are typically used in glass façades, as for instance in the "AXA" head office building located in "Galerie Hausmann" in Paris. The building has been designed by LAUBEUF SA; its façade is shown on figure 3.

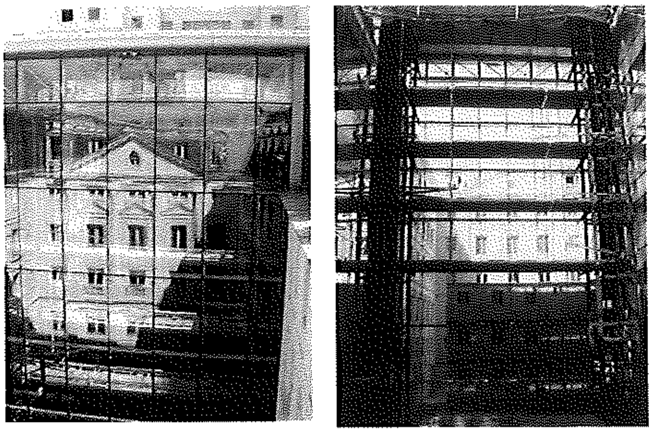

Figure 3. The "Axa" Building in Paris (LAUBEUF S.A.-2001)

The façade includes a truss-girder made of elliptical hollow sections (figure 4). The responsible authorities required a detailed justification of the strength properties used for design.

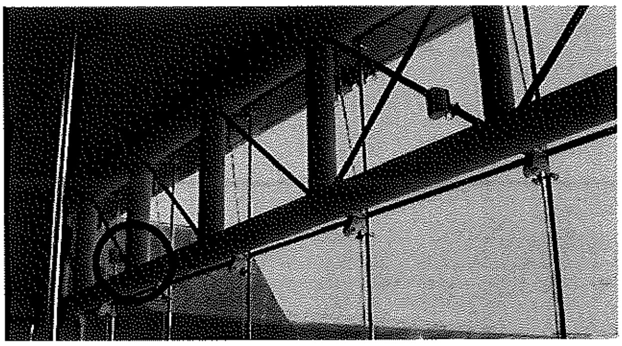

Figure 4. View of the studied joint in the truss-girder

2.2 *Definition of the joint.*

The studied joint (figure 5) connects three structural elements: a 12 mm thick 480x240 elliptical chord, a 4 mm thick circular diagonal member with a 60.3 mm diameter and a 8 mm thick 320x160 elliptical brace. All sections are made of S355 J2H steel grade. The load T_{Sd} acting on the tension member is equal to 121 kN while the brace is subjected to a compression force F_{Sd} of 85 kN and a bending moment M_{Sd} of 22 kNm.

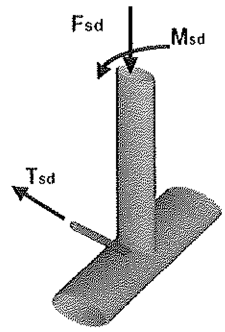

Figure 5. Studied joint

As Eurocode 3 does not provide information to evaluate the load-bearing resistance of such an assembly, the study was carried out in three steps:

- Extrapolation of Eurocode 3 rules,
- Numerical simulation,
- Experimental testing.

2.3 *Extrapolation of Eurocode 3 rules*

In a very preliminary step, "equivalent" rectangular (RHS) and circular (CHS) hollow profiles are substituted to the actual elliptical chord cross-section, as seen in figure 6. For such "equivalent" cross-sections, the strength of the considered assembly may be derived by means of Eurocode 3 Annex K. Two diameters may be selected for the "equivalent" CHS; Annex K strength evaluations have been carried out in both cases and the lowest calculated resistance has been kept.

What must be understood is that the word "equivalent" is inappropriate as no theoretical or even physical reason may be given to justify these calculations. But further on this paper, some comparisons between the actual strength of the studied joint and the estimated one will be carried out.

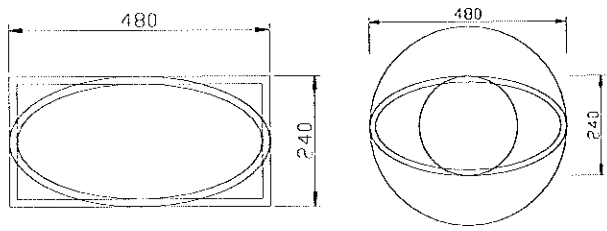

Figure 6. "Equivalent" R.H.S and C.H.S.

The results of the calculations are reported in the two first columns of figure 7 where λ is the estimated load factor at failure. In the third column, the plastic cross-sectional resistance of the connected elements is also indicated. According to this table, the failure should occur by yielding of the tension member, and not of the connections, for a load multiplier equal to 2.7 times the design loads.

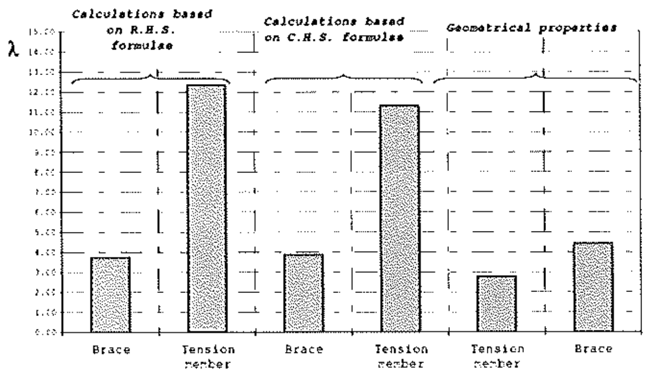

Figure 7. Failure load factor based on Eurocode 3 extrapolations.

2.4 *Experimental tests*

Three similar test specimens were tested (figure 8) at the Department M&S of the University of Liège. The brace was subjected to compression and bending, and the diagonal was subjected to tension, by means of three jacks. The joint was clamped to the ground and equipped with strain gauges and displacement transducers. Lime was also used to visualize the yielding all along the loading.

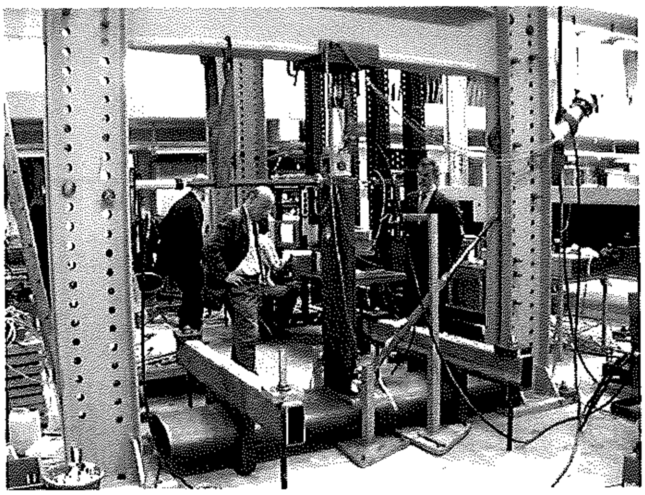

Figure 8. Test set-up

Because of the limited capacity of the jacks, the tests were stopped before a full rupture was reached in an element.

As can be seen from the curve depicting the "load factor as a function of the transverse displacement of the brace" (figure 9), the results of the three tests are rather well correlated between each other, although a slip occurred (upon test #3). At 1.7 times the design loads, no failure or major plastic deformation was observed.

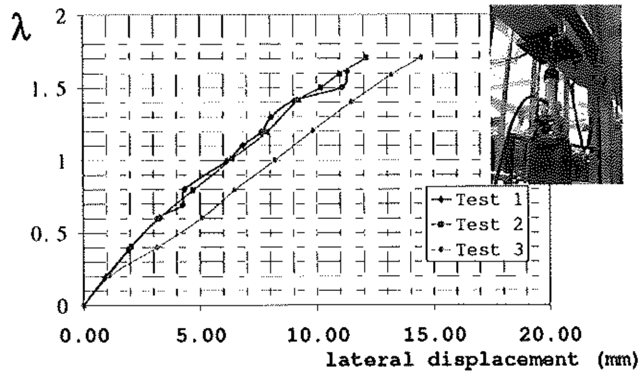

Figure 9. "Load factor-lateral displacement of the brace" curves

2.5 *Numerical study*

Further to the tests, a FEM numerical model based on 4-nodes shell elements (linear) was set-up on ABAQUS 6.1. (figure 10). All the material and geometrical non-linearities were integrated in the calculations. The material stress-strain laws were based on actual measured steel properties.

Symmetry was taken into account in the model, and the loads were applied by concentrated forces on nodes. For the sake of simplicity, the welds were not modeled.

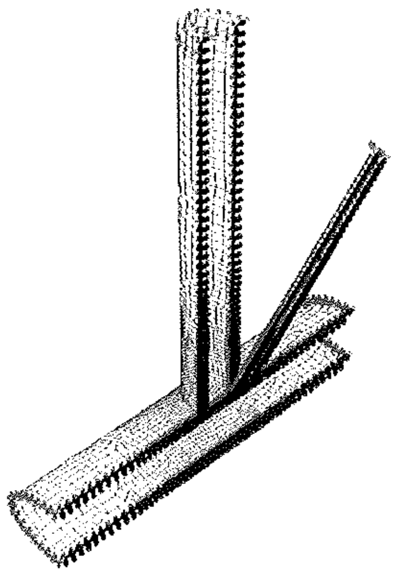

Figure 10. Numerical model

Although it exhibits less rigidity due to modeling conditions (figure 11), the numerical curve is in a satisfactory agreement with the actual behaviour of the structure up to 1.7 times the design loads. Beyond that multiplier, no experimental information is available, as already pointed out.

But from the numerical simulations, the effects of the geometrical non-linearities all along the loading may be observed.
-When only material non-linearity (i.e. linked to the material's properties) is considered, failure takes place at 270 % of the design loads (yielding of the tension member).
-When both material and geometrical non-linearities are taken into account, the so-called "P-Delta effects" reduce the resistance of the brace down to 240% of the design loads. Local second order effects also appear in the chord, but this will be discussed in another chapter of this paper.

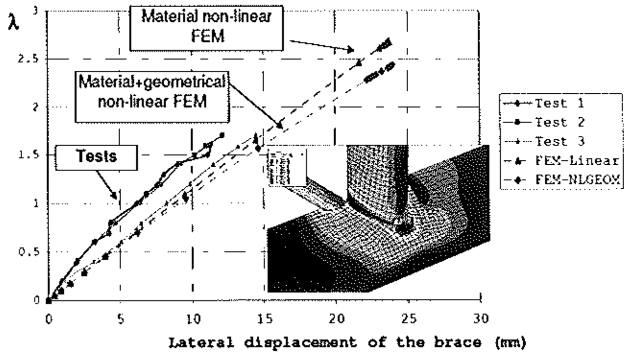

Figure 11. Effect of the geometrical non-linearity

2.6 *Conclusions of the case study*

Some conclusions related to the resistance of the structure to the design loads arise from this study. Numerical models reproduce rather well the actual response of the joint up to 170% of the design loads. No experimental information beyond this load level was obtained, but according to the simulations, the failure should occur at 2.4 times the design loads.

3 FUNDAMENTAL RESEARCHES

Further to this case study, far simpler cases were studied in order to better understand the behaviour of connections between elliptical hollow sections. The aims of this study were to investigate the physical behaviour of such joints, to develop reliable numerical models and to develop the basis of analytical formulations for evaluating the joint stiffness and resistance properties.
Simple assemblies subjected to compression and tension forces were selected. The chord and the brace were made from elliptical sections connected by welding at 90 degrees.
Two different joint configurations were considered (figure 12). They involved respectively:
- an 8 mm thick 320x160 mm elliptical chord;
- a more compact 8 mm thick 220x110 mm elliptical chord.
The braces were identical in both cases (4 mm thick 120x60 mm elements). The steel grade was S355 J2H. Two specimens from each category were subjected to tension, and one to compression.

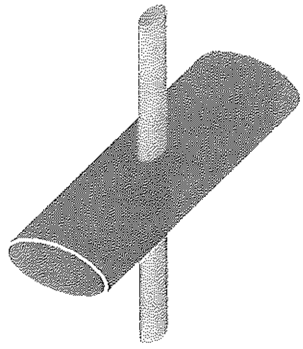
Figure 12. Simpler joints

3.1 *Experimental tests*

The tests were carried out at the University of Liège, using a 100 t press. The test pieces were equipped with displacement transducers and lime was again used. The aim of the tests was to observe the failure modes and the depict of the load-displacement curves, and to lay down the basis and reference for a numerical study as well.

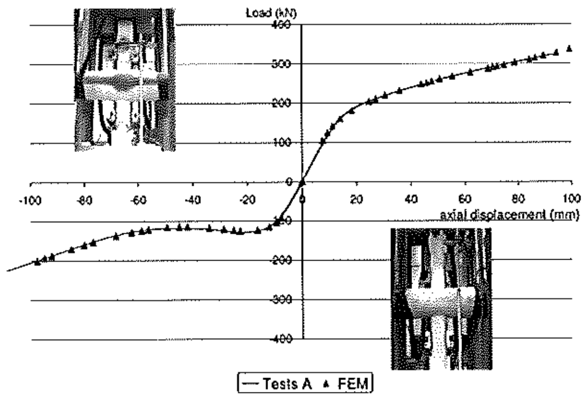

Figure 13. Experimental and numerical curves

Significant differences can be noted between tension and compression load situations, as seen in figure 13.
In the specimens subjected to tension, plastic hinges develop in the chord and progressively reduce the joint stiffness (knee in the load-displacement curve at figure 13). The later does not vanish because of the progressive development of strain-hardening and membrane effects resulting from the "ovalization" of the chord. Finally the brace fails by excess of plasticity in tension.
In compression, plasticity develops and also reduces the joint stiffness until a "snap through" phenomenon occurs, as a result of the local buckling of the chord (the brace "penetrates" into the chord). Thus the curve exhibits a local peak value. Later on

the joint stiffness progressively increases again; as in the first configuration, this phenomenon is linked to the development of significant membrane effects in the chord.
In both loading cases, the joint exhibits a quite large ductility.

3.2 *Numerical simulations*

On the basis of the measured steel properties and geometrical characteristics, different numerical models were calibrated (figure 13 and 14). The weld dimensions and strength hardening properties did not appear to influence the numerical response significantly. The major influencing factors are the length of the chord and, primarily, the geometrical non-linearities. The numerical models fit very well with the tests, as can be seen on figure 13.

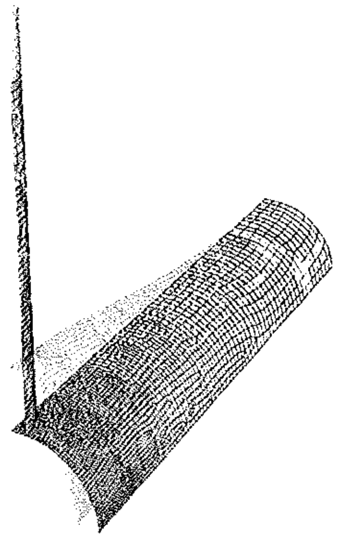

Figure 14. Numerical model of the simple joints

A parametrical study was then carried out. It resulted in quantifying the influence of various parameters on the behaviour of the joints. The ratio between the dimensions of the chord and the brace, as well as the thickness and the quality of the steel, were studied. The results of those studies will pave the way for developing analytical design formulae.

3.3 *Analytical studies*

In a first phase, an attempt to adapt existing resistance models to elliptical hollow sections may be planned. As far as the chord is concerned, failure may occur by yielding, buckling or by punching shear. For the brace, failure by yielding or buckling has to be contemplated.

For instance, the so-called " ring model" (figure 15) may be adapted to the yielding of the chord. But this requires evaluating the effective length of the chord on which the stresses could be assumed to be constant.

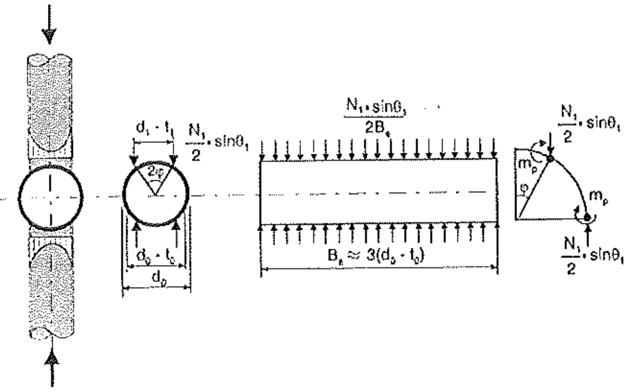

Figure 15. Ring model (adapted from Wardenier 2002)

For punching shear, available formulae may as well be slightly adapted for fitting the case of elliptical sections. And the yielding of the brace is simply calculated on the basis of the section properties.
Two analytical approaches may be followed:
- -a semi-empirical single formula in which all modes of failure and behavioural phenomena are included is derived, probably with different empirical values of the chord effective length according to the failure mode;
- -a more physical approach where three separate formulae are developed, each one with a clear physical background; that approach is conclusively selected as the reference for ongoing and future analytical developments.

As an example, figure 16 presents the strategy followed for the development of design formulae for chord resistance and stability. When no geometrical effects are taken into consideration, the failure of the chord results from the development of a plastic hinge mechanism in the chord. This plastic resistance is similar in both loading cases (compression and tension). As a first step, design formulae for the prediction of the plastic failure load need to be carried out. As discussed before, the geometrical non-linear effects lead respectively to a reduction and to an increase of this plastic resistance under compression and tension forces. This is illustrated in figure 16 through, a reduction factor k_{instab} and an increasing factor k_{memb} respectively.

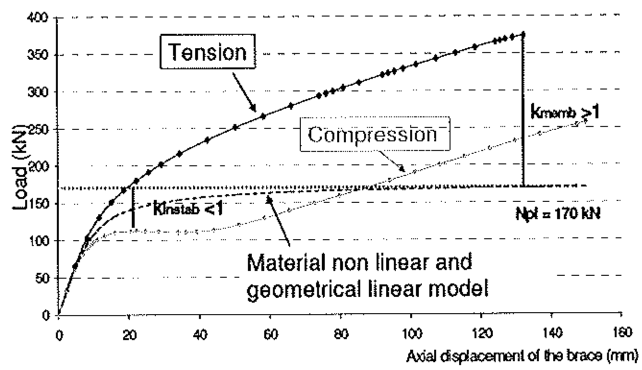

Figure 16. Illustration of the correction coefficients

So as to be able to predict the mode of failure and the level of resistance of simple brace-to-chord connections, analytical expressions for these two factors need to be proposed as a next step

In conclusion, this study on simple joints has permitted a better understanding of their behaviour in terms of failure modes, resistance and ductility. Numerical models were shown to be fully reliable and first analytical developments were initiated.

Soon new tests will be carried out to study the behaviour of joints belonging to trusses as shown on figure 17.

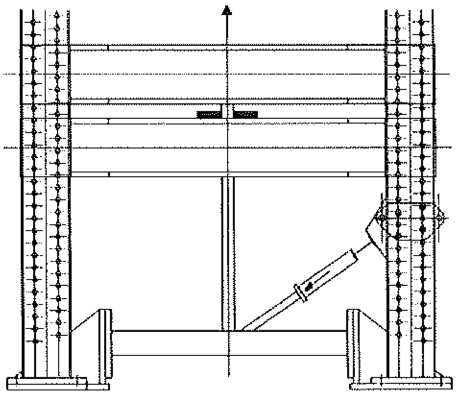

Figure 17. New tests to be carried out

4 CONCLUSIONS.

Preliminary experimental, numerical and theoretical studies were initiated and are aimed at developing adequate structural solutions for joints between elliptical hollow sections. The first results of those investigations are presented in the paper. Further research is planned in the forthcoming years; it should progressively lead to the proposal of practical design guidelines and recommendations for architects and designers interested in the use of such sections, whose architectural and structural benefits no longer need to be demonstrated.

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