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Effect of the Chord-Brace Angle on the Strength of Rectangular Hollow Sections K- and N-Joints in Galvanized Structures

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Abstract: An important consideration when using hot-dip galvanized tubular structures is the uncertainty of the joint behaviour due to the possible reduction in the global joint resistance produced by the vent holes required for the galvanizing process. This paper assesses the effect on the joint strength of the angle between the brace members and the chord in a K- or N-joints made with rectangular hollow sections. The study is focused on the case when those brace members include characteristic holes required for the hot-dip galvanizing process. To accomplish the objective of the proposed work, some tests on full-scale K- and N-joints, including angles of 35º, 45º, 55º and 90º, were carried out. The experimental work was complemented by a validated numerical simulation in order to give some design recommendations and to extend the research to other joint configurations.

Key words: Structural joints, tubular structures, galvanized structures, experimental tests, numerical simulation.

1. Introduction

It is known that structural hollow sections are always an excellent choice for trusses. When designing lattice girders, the option of CHS (circular hollow sections) provides a good structural behavior and good aesthetics. However, joints details require accurate profiling of the ends of CHS brace members and, therefore, higher fabrication costs. Thus, RHS (rectangular hollow sections) are more cost effective, combining the good structural behavior with joint details that only require flat cuts at the ends of brace members before welding their perimeters to the chord members. An important issue with steel structures is corrosion protection. Hot dip galvanization presents several advantages in comparison with other techniques but requires the provision of vent holes in the brace members. These vent holes must be large enough for optimization of the galvanizing process without reducing the strength of the joint. Therefore, an important consideration when using galvanized lattice girders has been the uncertainty in the joint behaviour due to a possible reduction in the resistance produced by the vent holes required for the galvanizing process.

Although there have been no failures attributed to vent holes, the lack of proper technical knowledge of this issue could limit the wider use of these tubular structures because there are no calculation procedures in design codes [1, 2] for the evaluation of the effect of holes on the joint capacity. In this situation, designers typically would over-size the brace member or they could change their mind and decide to use laminated open sections, whose behavior is well known, for steel structures that are designed to be galvanized. In order to answer these questions, given the concern of designers involved in this issue, a couple of projects funded by CIDECT (Comité International pour le Development et l'Etude de la Construction Tubulaire)

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and EGGA (European General Galvanizing Association) have been developed in the last few years.

CIDECT Project 14B [3] aimed to define how the holes should be executed and to propose some internationally accepted recommendations about the size, shape and position of vent holes. The holes were proposed on the basis of production efficiency and safety in the galvanizing plant hoping that the recommended size (between 20% and 25% of the diagonal of the cross section) and position (in the brace at a maximum distance from the chord of 18 mm) were also structurally appropriate. Following this, CIDECT Project 5BX [4] aimed to investigate through a combination of experimental tests and finite element modelling—whether the above recommended vent holes could have any adverse effect on the performance of the hollow section joints. One of the main variables taken into account in CIDECT Project 5BX was the angle between the brace member and the chord in order to evaluate its influence on the joint strength. This paper is focused on presenting and analyzing the results of this part of the research.

2. Experimental Method

2.1 Tested Joints

As mentioned above, rectangular hollow section K- and N-joints that are widely used in hot dip galvanized steel trusses are considered. For the typical K-joint of a Warren lattice girder, three different angles of 35º, 45º and 55º between the braces and chord have been investigated. Also, the N-joint that appears in other lattice girder configurations was considered. In this case, the non-symmetrical joint included a brace that was perpendicular to the chord and a diagonal with a 35º angle. To address the objectives, joints with and without vent holes were tested. The above recommended size, shape and position of the vent holes needed for the galvanization process were considered.

Four full-scale joint specimens were tested for each one of the four sets of joints considered. Two of them included the vent holes and another two did not have holes. This meant a total of 16 tested joints. All the joints had a common gap of 15 mm between the brace members and RHS 150 mm × 100 mm × 5 mm for chords and SHS (Square Hollow Sections) 100 mm × 3 mm for the braces. The vent holes diameter was 35 mm. Three specific specimens were galvanized prior to testing in order to check if this condition had any influence.

Although the steel grade was the same (S275) for all the hollow sections, in order to take into account the actual material properties, particularly in the later numerical simulation, it was necessary to carry out some standard tensile tests. Three coupons were produced from different faces of all the cold-formed hollow sections.

2.2 Test Procedure

To carry out the experimental program, a purpose-built test frame was used. Some recommendations for tests on these types of connections [5, 6] were taken into account. Figs. 1 and 2 show the test configurations for the K-joints with an angle of 45º and for the N-joints. Several attachments were specially designed and manufactured to accomplish the required angles for the four sets of joints. A hydraulic jack loaded the vertically positioned

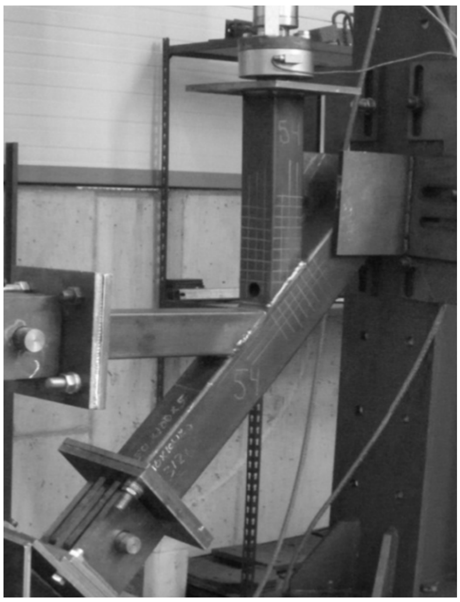


Fig. 1 Test configuration for K-joints.

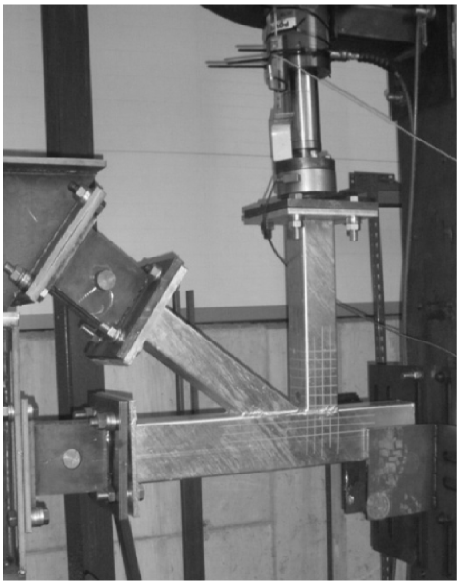


Fig. 2 Test configuration for N-joints.

brace member while one end of the chord was left free, in-plane and the other two ends were pinned to ensure that predominantly axial forces were transmitted to the members. The displacement in the loaded brace member was measured by a LVDT (Linear Variable Different Transformer) transducer allowing plotting of the force-displacement curves.

The load through the actuator over the vertical brace member was increased until failure of the joint. The tests were displacement-controlled and the registered collapse load was the maximum value of the force-displacement curve.

2.3 Test Results

Fig. 3 shows the experimental force-displacement curves obtained for the three sets of K-joints with angles between braces and chord of 35º, 45º and 55º, respectively. Letter H indicates that the joint tested included a vent hole. Fig. 4 shows the curves for the set of N-joints in which the diagonal angle was 35º. In these figures, the letter G indicates that the joint was galvanized before testing.

Figs. 5 and 6 show the most common failure mode that occurred in the tested K-joints and N-joints in both situations, with and without the vent hole.

3. Numerical Simulation

As well known, laboratory work is expensive and usually, the test program must be limited. So a numerical simulation followed the experimental tests to complement them. The aim of this part is the validation of the FE (finite element) analysis in order to be able to extend the research to other joint configurations, including some non-symmetrical joints.

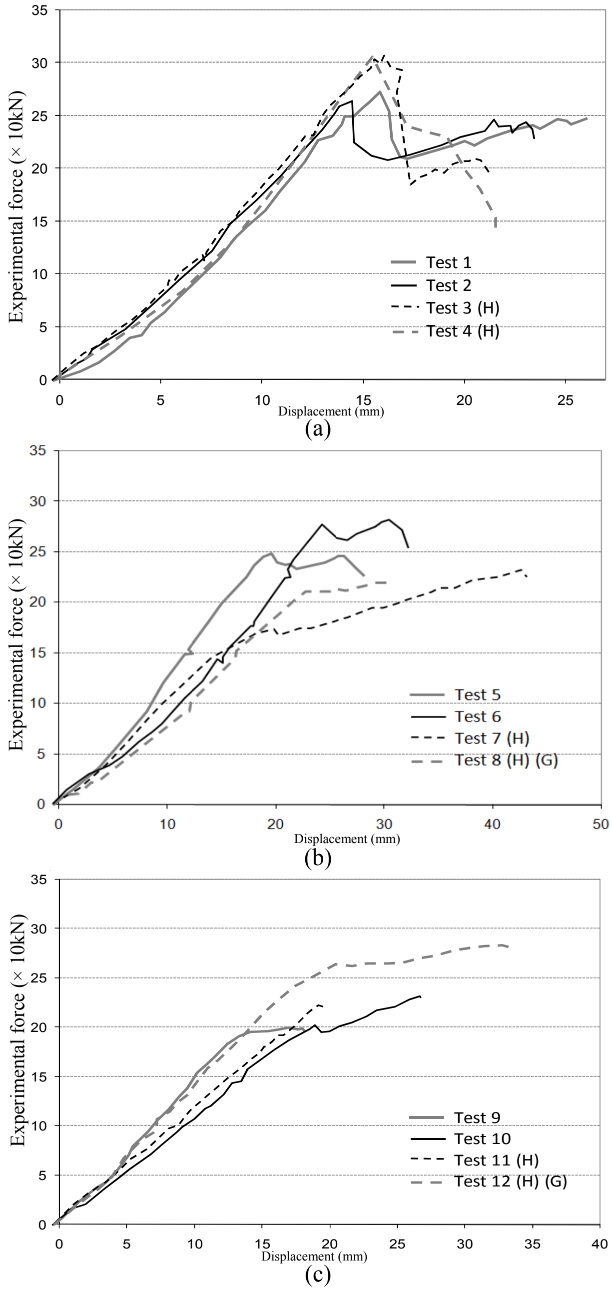


Fig. 3 Curves for K-joints: (a) 35º; (b) 45º; (c) 55º.

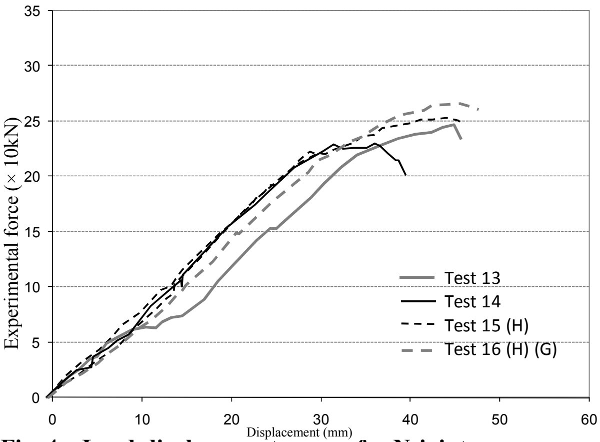


Fig. 4 Load-displacement curves for N-joints.

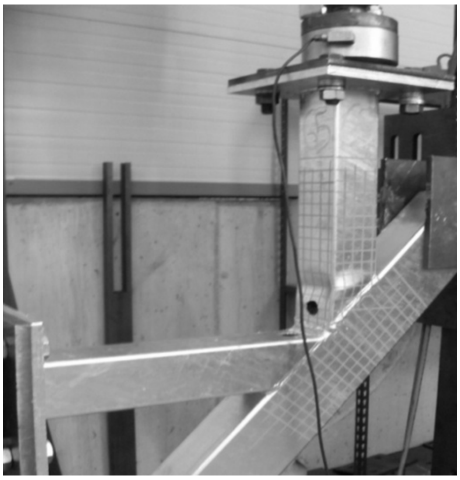


Fig. 5 Failure in a galvanized 45º K-joint.

Fig. 6 Failure in a N-joint without the vent hole.

The FE software ANSYS Workbench V.13 academic research was used for a parametric study or different joint configurations. The selected elements in the model were a four-noded shell 181 with six degrees of freedom at each node. Two different element sizes of 10 mm in the finer mesh area and 20 mm outside this area were taken in order to adjust the size of elements to the necessities of the simulation. Fig. 7 shows a meshed model of each set of joints considered in this work: K-joints with 35º, 45º and 55º and N-joints.

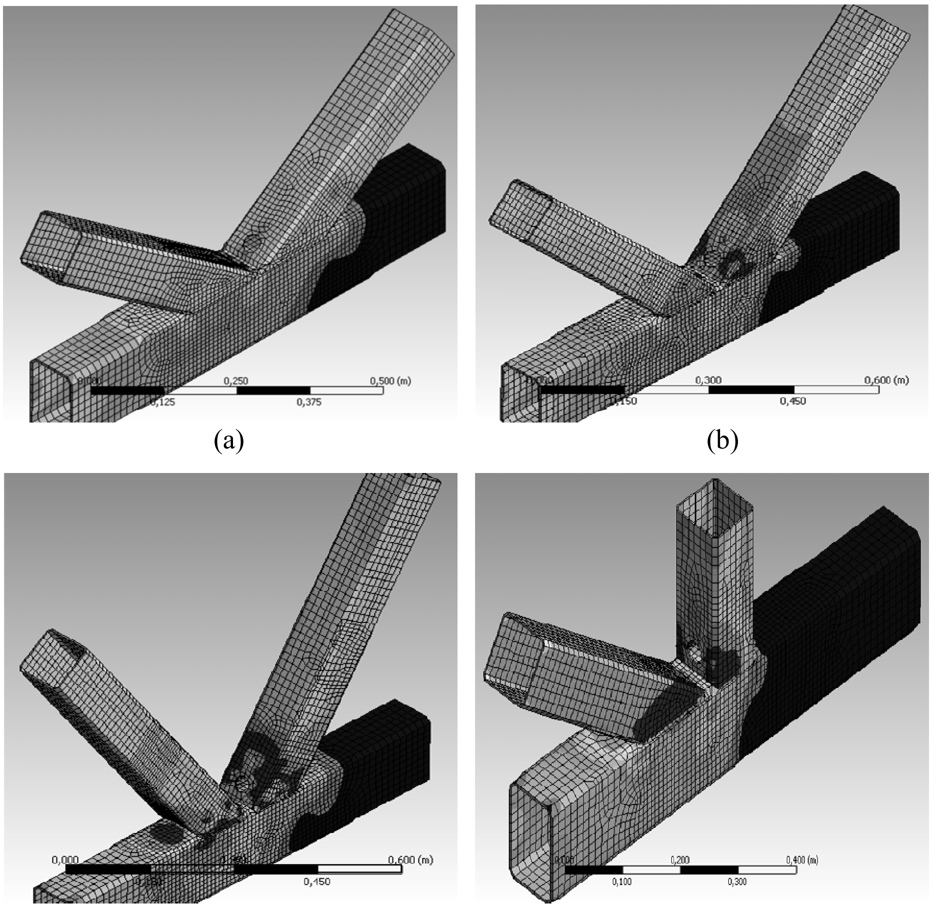
Using the actual material properties obtained in the standard tensile test, a non-linear analysis was carried out taking into account geometric non-linearities, non-linear material properties and non-linear buckling. An initial imperfection was selected according to the recommendations by Schafer and Peköz [7].

In order to reproduce the laboratory tests as faithfully as possible, the joint was loaded by small steps of displacement on one of the brace members. The other brace member and one end of the chord were pinned. The other end of the chord remained free to move in the load plane. Stresses, buckling modes and ultimate loads were calculated and their results were compared with the experimental tests, allowing validation of the model to extend its application.

Once the FE model was validated, it was extended to other joint configurations. In this sense, there was a concern about the behavior of some asymmetric joint configurations. This part of the study was specifically aimed at non-symmetrical joints of lattice girders in which the size of the tensile brace member is smaller than the compression brace member. Under these circumstances, it is possible that the smaller section of the tensile brace member leads to failure in this brace instead of the previously studied failure in the compression member.

For an initial insight into this situation, some numerical simulations were carried out. The considered joint configurations for this part of the research are shown in Table 1. As a starting point, the experimental and numerical results of the sets of joints KGP04 from the CIDECT Project 5BX [4] were taken.

For non-symmetrical joints, four configurations with different brace angles were considered. All of them had the same chord and compression member as in KGP04



(a) (b)

(c) (d)

Fig. 7 Numerical models for three K-joints (a) 35º, (b) 45º and (c) 55º, and (d) the N-joint.

Table 1 Maximum strength (kN) obtained in the FEM (finite element model) for non-symmetrical joints.

Joints reference	Chord (mm)	Compression brace (mm)	Tension brace (mm)	Brace angle	Without hole (kN)	With hole (kN)
KGP04 test	150 × 100 × 6	90 × 5	90 × 5	35º	452.46	453.22
KGP04 FEM	150 × 100 × 6	90 × 5	90 × 5	35º	446.89	446.63
Joint 1	150 × 100 × 6	90 × 5	60 × 4	35º	430.82	418.08
Joint 2	150 × 100 × 6	90 × 5	60 × 4	45º	374.81	361.61
Joint 3	150 × 100 × 6	90 × 5	60 × 4	55º	351.43	331.43
Joint 4	150 × 100 × 6	90 × 5	60 × 4	90º-35º	248.96	222.39

but a smaller tensile member of SHS 60 mm × 4 mm. Table 1 shows the maximum strength obtained for joints with and without the vent holes and Fig. 8 shows, respectively, two meshed models for a K-joint and an N-joint in the non-symmetrical simulation.

4. Discussion

A range of results has been produced for this paper, including experimental tests on four sets of joints with different brace angles, a complete numerical simulation of all the joints and an additional numerical simulation for non-symmetrical joints. These results are presented and compared in this section below. Fig. 9 shows the maximum load in joints without any hole against the same joint with the vent hole, for both experimental and numerical simulation results. The vicinity of the plotted points to the diagonal lines concludes that there are no significant differences between both.

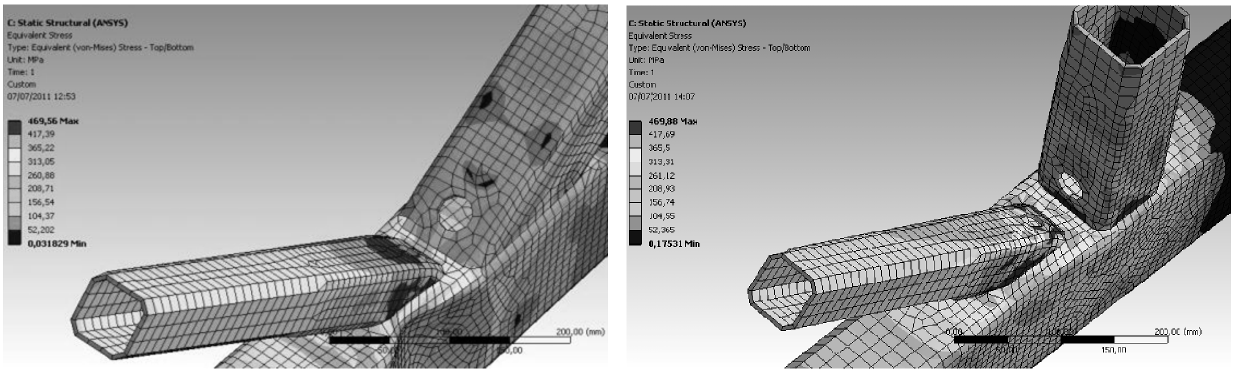


Fig. 8 Different angles in FE simulation for non-symmetrical joints.

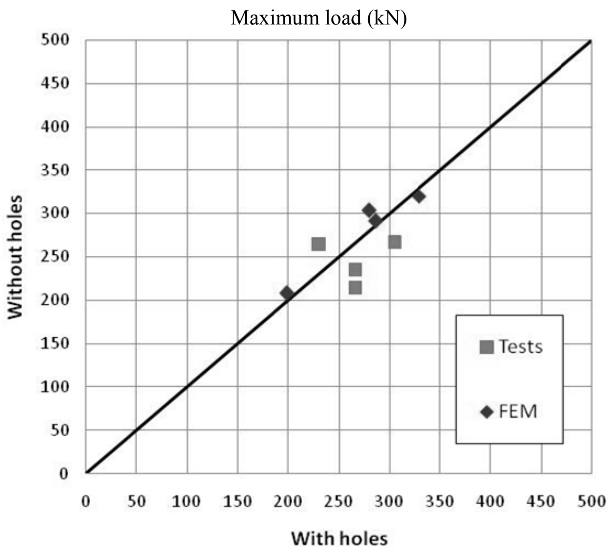


Fig. 9 Maximum load in joints without holes vs. with holes.

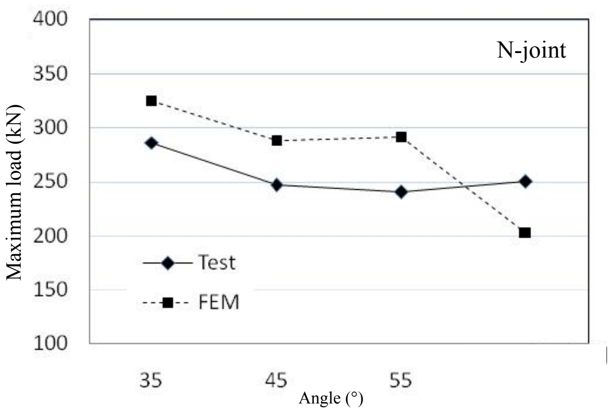


Fig. 10 Comparison test—numerical simulation.

Having assumed that there is no influence from the vent holes, Fig. 10 shows the maximum load for the joint tested with different brace angles. Every plotted point represents the mean value of the obtained data by FEM or by test. The plotted results allow a clear comparison of tests and simulation and indicate that there is a reasonable agreement and, therefore, the method for the finite element modelling can be considered validated. From this figure, it can be concluded that the resistance of K-joints is lower as the brace angle gets bigger.

Fig. 11 presents a comparison of FE results and EC3 equation results for the four sets of joints taken into account in this research when a nominal steel S275 is considered. A good agreement is observed and a clear conclusion indicates the lower resistance in joints when the brace angle gets bigger. It is important to note that when the failure mode is a local buckling in the BF (brace member), the angle has no influence according to EC3 equations. In fact, the observed influence of the angle in EC3 is due to the fact that the predicted failure mode by equations is a CP (chord plastification) and in this case, the angle would have an influence. However, the results of the experimental tests and numerical

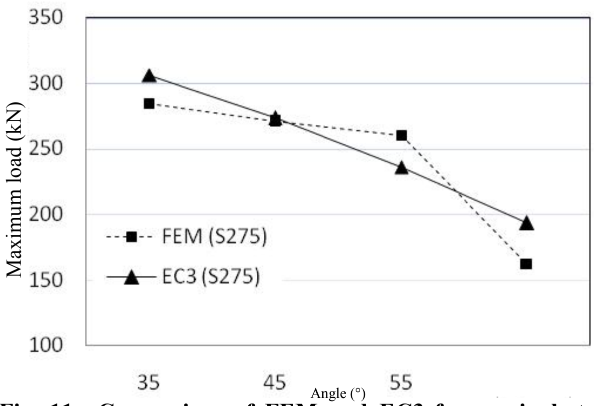


Fig. 11 Comparison of FEM and EC3 for nominal steel S275.

simulation indicated for all the tested joints a failure by local buckling in the BF instead of CP.

The situation is not so clear for N-joints. From FE and EC3 proposals, resistance is even lower than K-joints with the bigger brace angle, nevertheless, test results indicate that there is not a significant reduction.

In the case of non-symmetrical joints with different cross sections for the tension and compression brace members, Table 1 allows a quick comparison of the results obtained just in the FE simulation. Again, there is no significant influence of vent holes on the ultimate load of the joint. Also, it can be observed that, independently of the joint presented a vent hole or not, the maximum strength that the joint was able to reach decreased as the brace angle increased. Here, the analyzed N-joint followed the same pattern observed above by FE and EC3.

5. Conclusions

Once the experimental and numerical results have been presented and discussed, the following conclusions can be drawn from this work:

(1) From the experimental programme and from the numerical simulation, it can be concluded that there is no influence of vent holes on the behavior and strength of the tested joints;

(2) For symmetrical K-joints in Warren lattice girders, the joint resistance decreases as the angle between the brace member and the chord increases. In case of N-joints, some more results are needed;

(3) A reasonably good agreement was obtained when tests and finite element model were compared, allowing to use the numerical model to predict the non-symmetrical joints behavior;

(4) EC3 equations predict quite well the strength of the joints but not so well the failure mode. It would be necessary to take into account the change in the brace failure equation to the angle between braces and chord in order to predict accurately both resistance and failure mode;

(5) In case of the studied non-symmetrical joints, it can be said again that there is no influence of vent holes. It can be also concluded that the K-joints present a lower resistance when the angle between braces and chord increases.

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