Experimental evaluation, FEM and condensed stiffness matrices of 2D external welded haunched joints

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Abstract.

In recent years, several researchers have been working hard to improve the knowledge with respect to steel joints behaviour. Special effort has been made for obtaining the stiffness of the different components of the joints, with the aim of introducing this stiffness in the component method in accordance with the EC3. Nevertheless, the component method has important limitations and therefore it is necessary to develop new methods for obtaining the stiffness of joints.

In the present work, an alternative method of evaluating the stiffness of 2D external welded haunched joints is presented. The authors show the results of 4 tests and their corresponding finite element models. Four different typologies of joints have been tested, in regards to the stiffening of the column web. The four configurations of joints are the following:

Joint 1: with three horizontal stiffeners in the column web.
Joint 2: with two horizontal stiffeners and an inclined stiffener in the column web.
Joint 3: with two horizontal stiffeners in the column web.
Joint 4: without web stiffeners.

In all cases, the specimens have been subjected to a point load at the end of the beam, and rotations and displacements have been measured.

Additionally, finite element models of the joints have been developed, and they have been properly calibrated with the results obtained in the tests. The condensed stiffness matrices of the joints have been extracted, and they have been tested by means of introducing such matrices into the global analysis of 4 frames, and comparing the obtained results with those ones extracted from the corresponding finite element models. The use of the condensed matrix of the joints presents very good results, and takes into account all the interactions between the different degrees of freedom of the joint.

Keywords: Semi-rigid joints; Haunched joints; Condensed matrix;

1. Introduction

In recent years there has been an important improvement in the study of steel joints. Proof of this progress is the inclusion of a specific code in the EUROCODE 3 [1] and [2]. The methodology used for obtaining the stiffness of the joints is the component method. This method requires the division of the joint into several components, whose individual stiffness is calculated analytically, and they are subsequently assembled as interconnected springs. Therefore, it is necessary to study these components, and several authors have done important work in this direction in the last years. Bayo et al. [3] and Lopez et al. [4] have been working in the study of the shear behaviour of trapezoidal column panel. Loureiro et al. [5] have studied the shear behaviour of stiffened double rectangular column panels. Liang et al. [6] have made a comparative study on tensile behaviour of welded T-stub joints for high strength steel under bolt preloading cases. Gil et al. [7] have presented the results of a study for major axis steel joint under torsion, and their stiffness and strength characterization.

The introduction of the stiffness of joints in the overall analysis is very important, as shown for authors as Frye and Morris [8] who analyze flexible connected steel frames, Chen [9] with his

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practical analysis for semi-rigid frame design and Faella et al. [10] that have studied structural steel semi-rigid connections. Elflah et al. [11] study the structural behaviour of six full scale specimens of stainless steel including flush plate joints, top and seat cleat connections, and top, seat and web cleat. Szafran et al. [12] show the results of the analysis of structural joints consisting in a full-scale pushover test of a 40 m high lattice tower.

However, the component method shows significant difficulties in its implementation in the overall calculation of the structure, such as the inability to capture the interaction between the different degrees of freedom of the joint, the difficulty for determining the stiffness of certain components, and finally, it leads to a single rotational spring to simulate the joint behavior, which is a rather simplistic model of the joint stiffness. For this reason, alternative methods to the component method must be sought. Some work has been done by Chen et al. [13], Pecce et al. [14], Pitrakkos et al. [15], Saravanan et al. [16] and Sulong et al. [17] with the aim of obtaining alternative simplified methods and models for the calculation of initial stiffness of the joints. An important step in this direction was given through the development of the cruciform element to model semi-rigid composite connections and 2D steel joints in the works of Bayo et al. [18] and [19]. Zhu et al. [20] have proposed a generalized component model for structural steel joints. The wide variety of joints both in 2D and 3D make it necessary to go further in the search for an alternative method to the component method. One possibility would be the use of meta-modeling methods as those indicated for Dias et al. [21] or the use of neural networks as Kim et al. [22], who use a neural network approach for extracting a model from experimental test data. Sundar et al [23] propose a method for Kriging's model development derived from the associated model probabilities. Zhang et al. [24] present an effective active-learning based Kriging's method for structural reliability analysis. Recently, Bayo and Gracia [25] have proposed to obtain the condensed stiffness matrices of 2D welded symmetric joints by means of the meta-modelled of their mode shapes using the Kriging's method. Loureiro et al. [26] have presented a wide parametric analysis of asymmetric welded steel joints, and have meta-modelled the stiffness matrices in a direct mode, using the same Kriging's method.

To carry out these studies in the area of the structural analysis of joints, it is necessary to have large databases. The first step consists of testing real joints. Then, finite element models properly calibrated can be generated, in order to carry out a parametric study. The obtained database will form the basis for the subsequent treatment of such data in order to be able to estimate the stiffness of joints.

This article presents the results of four tests of 2D external welded haunched joints. These joints are formed by HEA 200 columns, with haunched IPE 300 beams with different settings in regards to the number and disposition of the stiffeners. The tests have been modelled using Abaqus software with the aim of obtaining calibrated finite element models that will allow a parametric study in the future. Additionally, a study of stiffness and resistance of the analyzed joints have been carried out.

The approach to be pursued is the modelling of the joint by means of its condensed stiffness matrix. This matrix, with 9 degrees of freedom, has been obtained by static condensation of the complete stiffness matrix of the finite element model of the joint. The results of using the condensed stiffness matrix has been compared with those extracted from FE models with good results.

2. Tests results

In the present work, with the aim of analyzing representative configurations of 2D external welded haunched joints, the four models showed in Table 1 have been defined and tested. Figure 1 shows the sketches of the four tests with details of thickness and dimensions of beams and columns. The dimensions are expressed in millimetres.

Table 1. Configuration of the tests

Test	Column	Beam	Shear Panel Stiffener	Horizontal stiffeners
1	HEA 200	IPE 300	None	3
2	HEA 200	IPE 300	Yes	2
3	HEA 200	IPE 300	None	2
4	HEA 200	IPE 300	None	None

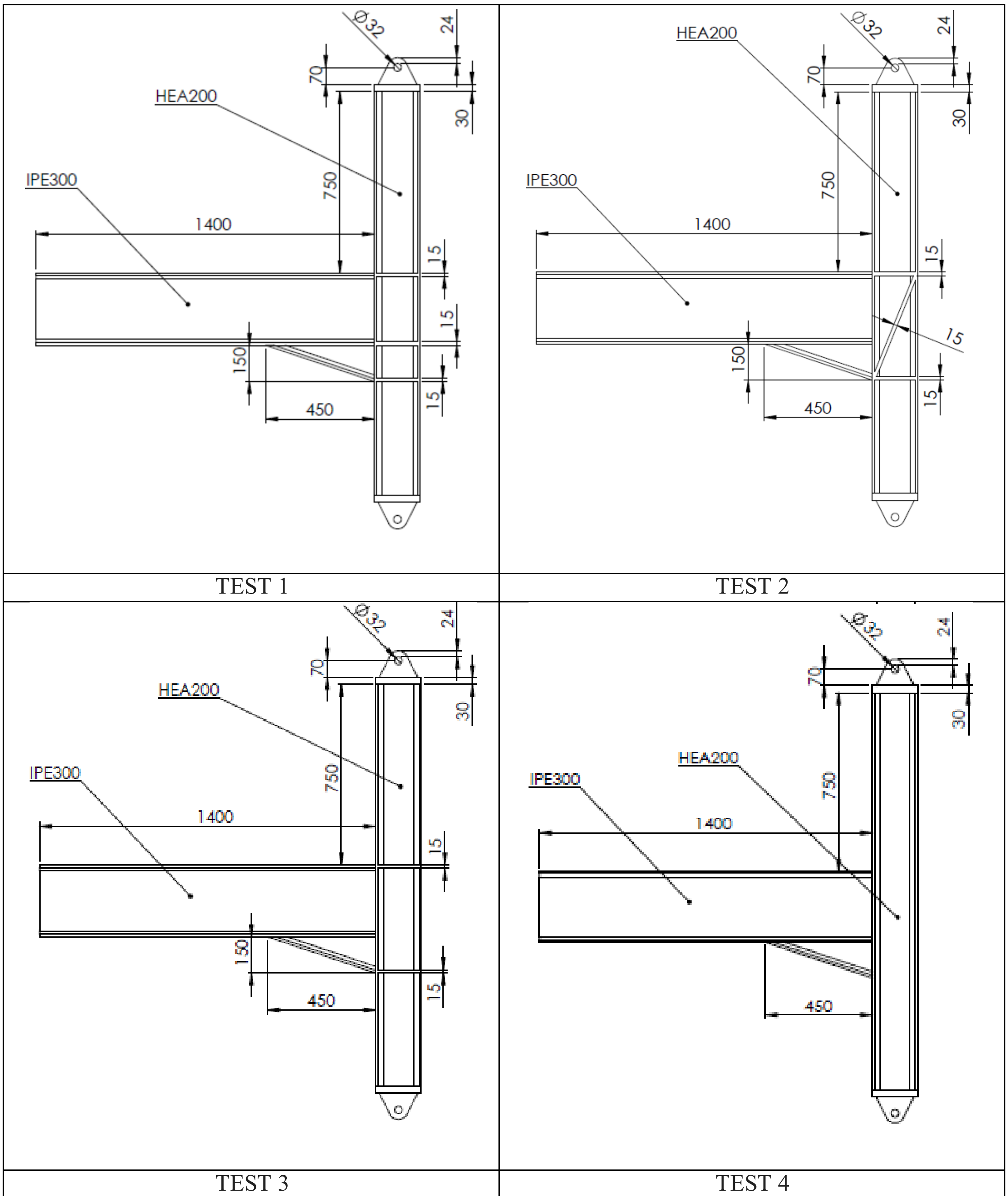


Fig. 1 Sketches of the tests

As noted previously, in all cases the columns are HEA 200 and the beams are haunched IPE 300 hot rolled profiles. Model 1 consists of 3 horizontal stiffeners, one at the height of the top flange of the beam, another at the height of the lower flange, and finally, a third stiffener at the height of the haunch flange. Model 2 has an inclined stiffener in the column web panel, and two horizontal stiffeners in the upper and lower part of the joint, respectively. The third joint consists of two horizontal stiffeners, one at the height of the top flange of the beam and the other at the height of the lower flange of the haunch. Finally, the model number 4 does not use any type of stiffener. In all cases, the stiffeners thickness is 15 mm. The material is a S275 steel, whose characteristics, extracted from coupons, are shown in table 2.

Table 2. Mechanical characteristics of the material

Element	f_y (MPa)	f_u(MPa)
Columns	326	467
Beams	321	457
Stiffeners	318	462

As it can be seen, a wide range of configurations has been included, in order to determine the influence of the stiffeners on the behaviour of the joints. In all models, the length of the column is 1870 mm, and the total length of the beam is 1400 mm. The tests have been conducted in the Laboratory of Structural Analysis of the High Polytechnic School of the University of A Coruña. Figure 2 shows photographs of the four tests.
The rotations of the joints have been measured by means of two horizontal inclinometers located in the column and one vertical inclinometer situated in the beam, as shown in Figure 3(a). The top and bottom inclinometers placed on the column (Inclinometers 1 and 2, respectively) measure the rigid body and bending rotation of the column, while the vertical inclinometer (Inclinometer 3) measures the rotation of the beam in that section. The rotation of the joint (Φj) has been obtained by subtracting from the reading of the Inclinometer 3, the average of the readings of Inclinometers 1 and 2, as indicated in equation 1, where Φ_1, Φ_2 and Φ_3 are the rotations of inclinometers 1, 2 and 3 respectively.
The loading process has been carried out by means of a hydraulic cylinder. This force has been applied at a distance of 1 m from the column flange and it has been measured by means of a load cell situated in the upper end of the cylinder.

$$\emptyset_j = \emptyset_3 - (\emptyset_1 + \emptyset_2)/2 \qquad (1)$$

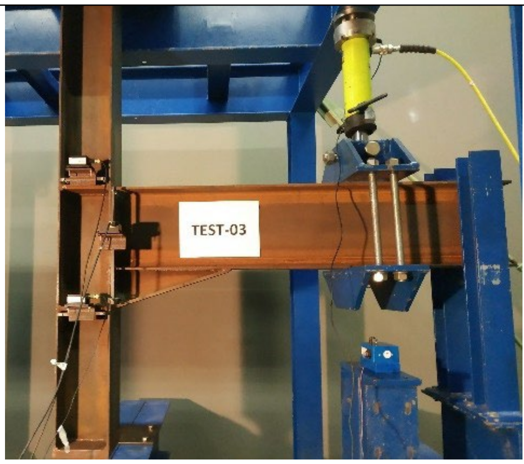
Additionally, a displacement sensor has been placed at the point of application of the vertical force, as shown in Figure 3(b). In all cases, a first step consisting of a preloading and unloading process has been done. This process has the objective of adjusting the possible clearances between the different elements that form the tests, as well as verifying the correct performance of the measuring equipment. It has been carried out in a single cycle of loading and unloading, reaching a maximum force of 20 KN in all cases. Once it has been verified that everything works correctly, the tests have been performed. The maximum loads applied to the four joints are shown in Table 3. The obtained moment-rotation curves for the different tests and their initial stiffness values are shown in Figure 4 and Table 4, respectively. In all cases the curves present an initial lineal behaviour, and the tests have been conducted until the non-linear zone of the corresponding moment-rotation curve has been reached.
As it can be seen, the number of horizontal stiffeners has very little influence on the moment-rotation curve of the joint, although the initial stiffness increases very slightly as the number of horizontal stiffeners does. Nevertheless, the addition of the diagonal stiffener in the column web panel leads to a significant increase of about 67 % in the stiffness of the joint. This fact shows the importance of the web panel in shear in the stiffness of the joint, as indicated by [3], [4] and [5].

Table 3. Maximum load applied to Tests

Test	TEST 1	TEST 2	TEST 3	TEST 4
Maximum load (KN)	144	280	128	121

TEST 1

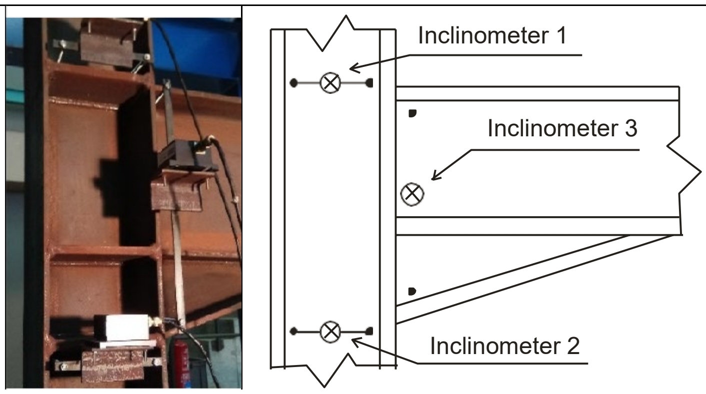
TEST 2



TEST 3

TEST 4

Fig. 2 Tests configuration



(a)

(b)

Fig. 3 Sketch and test disposition of Inclinometers (a), and piston, load cell and displacement sensor (b)

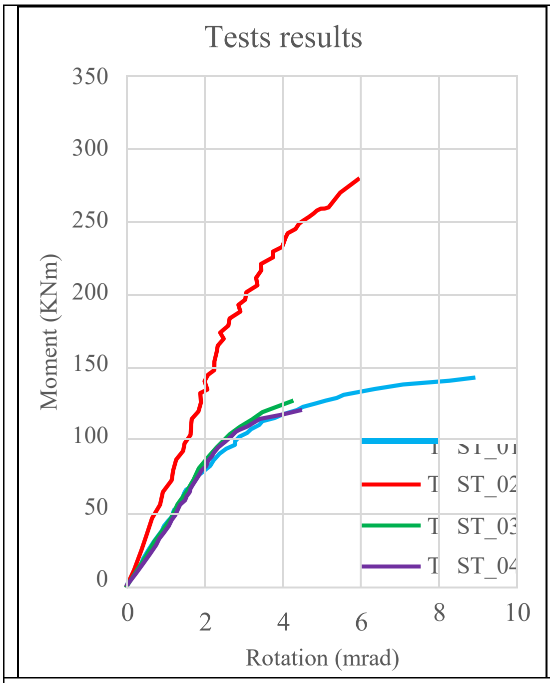


Fig. 4 Comparative Moment-rotation curves

3. Numerical models of the joints

The results of the tests have been used to calibrate the finite element models whose characteristics are described in the next paragraphs. The commercial program Abaqus has been used, and the Figure 5 shows global views of the four models. 3D elements C3D8R with reduced integration have been used. The average number of elements and nodes per model are 24,500 and 35,300, respectively. The average size of the elements is 10 mm. The real stress-strain curve of the material, including plastic hardening, has been introduced into the FE model. The adopted values of yield (f_y) and ultimate (f_u) stresses are shown in Table 2. The values adopted for the elastic modulus E and the Poisson ratio ν were 210,000 N/mm^2 and 0.3, respectively

The load has been applied by means of displacement control method applied to the vertical displacement at the end of the beam, at the same distance (1 m) from the column flange at which the load has been applied in the tests. The boundary conditions were similar to the test's ones, although only one half of the tests have been modelled. Symmetry conditions in the middle plane of the webs have been applied, both for column and beam, as it can be shown in Fig 5. Figure 6 shows a global view of the four models with the map of the Von Misses stress, with a loading level similar to the maximum load reached in the tests.

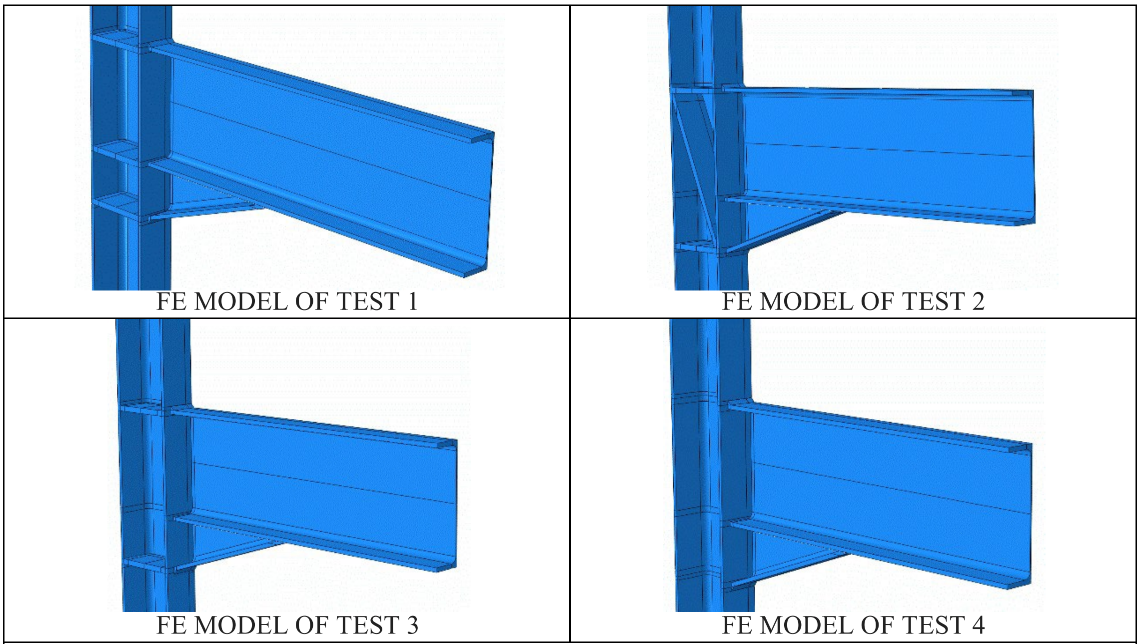


Fig. 5. FE models of the joints

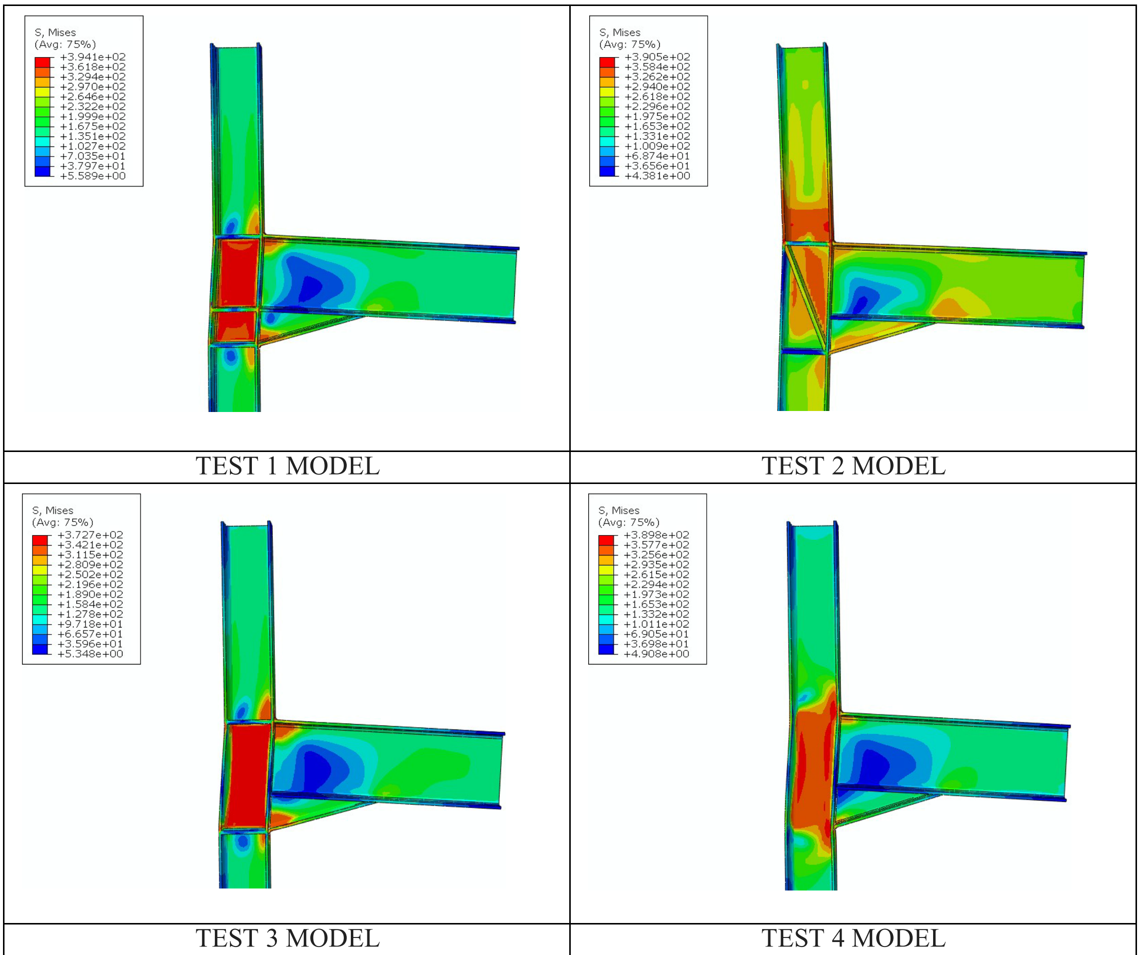


Fig. 6. Von Misses stresses at the end of the loading process

Rotations and bending moments have been extracted from FE models, and the corresponding M-Φ_j curves are shown in Figure 7. The comparison between FEM and Test results can be seen in Figure 8. Table 4 shows the comparison between the values of the initial stiffness of the tests and the FE models. The obtained results show that the finite element models correctly replicate the behaviour of the tests.

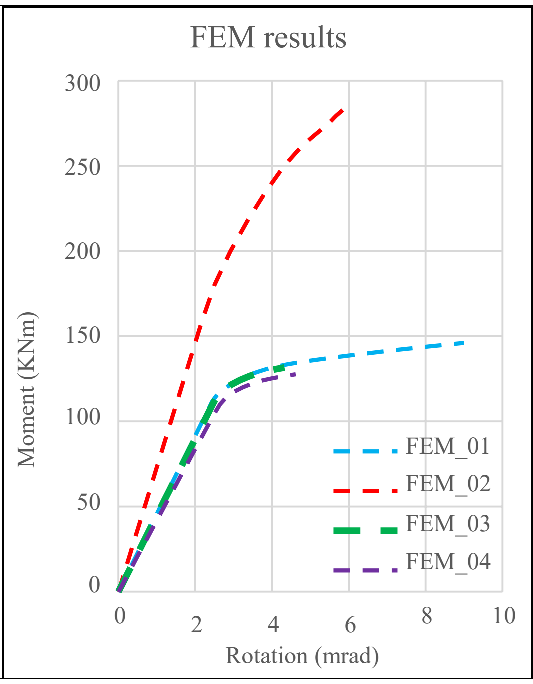
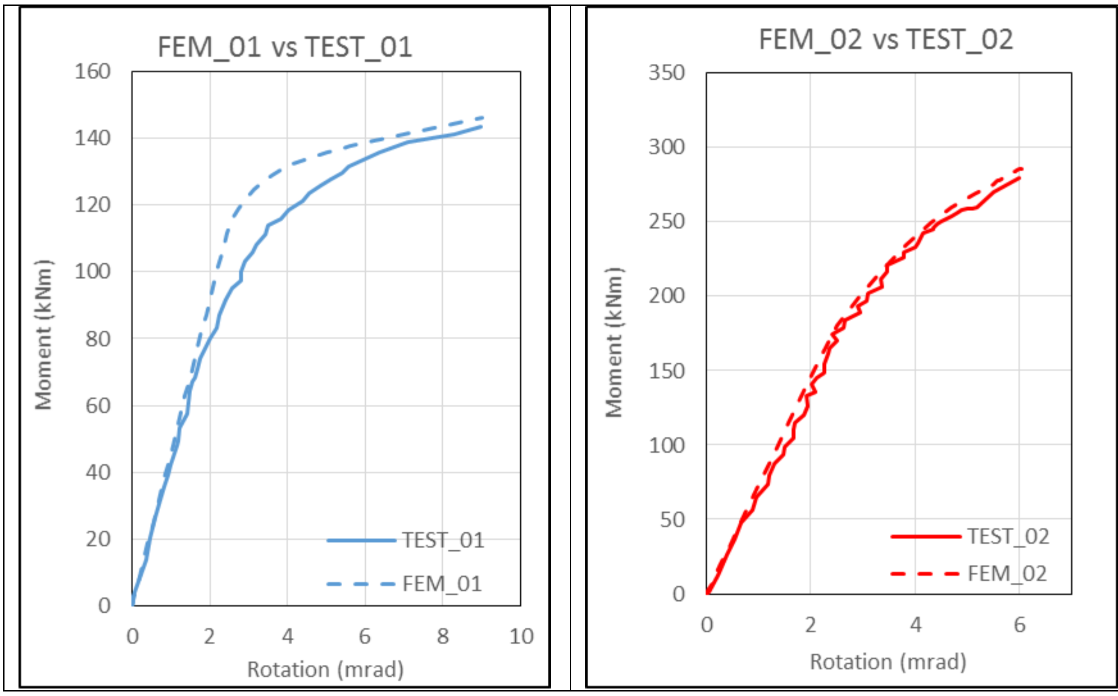


Fig. 7. Comparative moment-rotation curves for FEM models



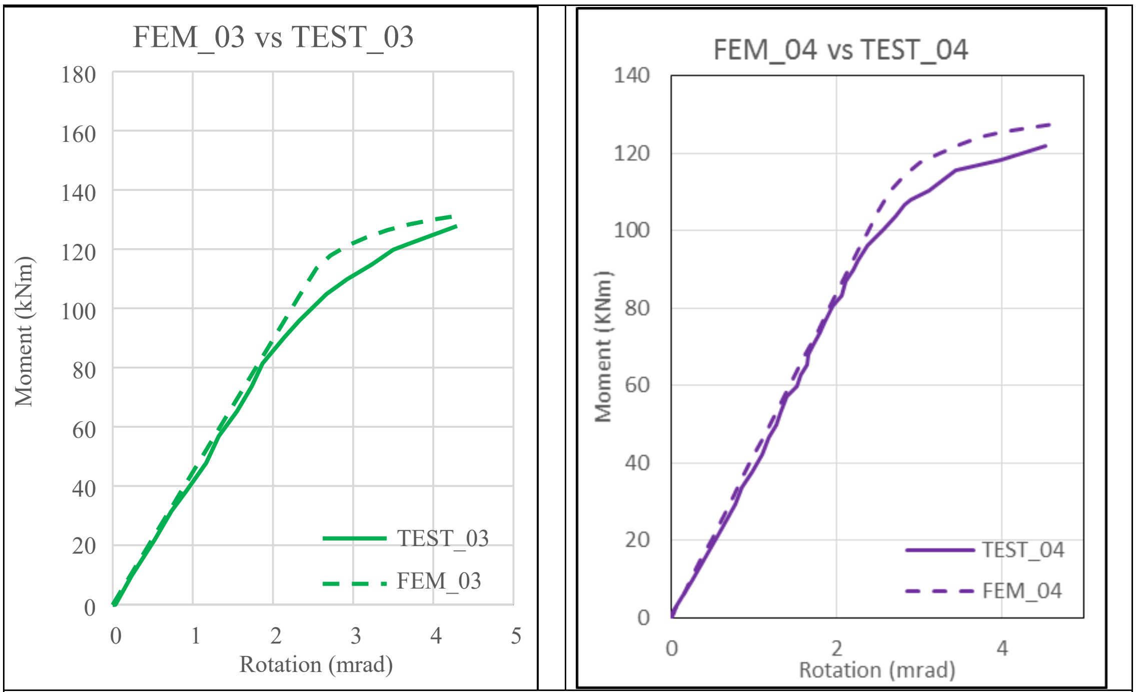


Fig. 8. Comparative M-Φ_j curves between FEM and Tests

Table 4. Initial Stiffness for FEM models and Tests

Model	$K_{i,Test}$ (KNm/mrad)	$K_{i(FEM)}$ (KNm/mrad)	Error (%)
Model_01	43.40	45.81	5.55
Model_02	72.09	72.14	0.07
Model_03	42.64	44.83	5.14
Model_04	41.23	41.88	1.57

In order to a better characterization of the joints, a study of their resistance has been carried out, and the corresponding joint moment resistance ($M_{j,Rd}$) has been obtained. The intersection of the trend lines of the linear and plastic zones of the M-Φ_j curves determines the value of $M_{j,Rd}$, as illustrated in Figure 9. The obtained results are summarize in Table 5, and present a similar behaviour that those obtained for the stiffness study. The horizontal stiffeners have a very little influence in the resistance of the joint. Nevertheless, the diagonal stiffener leads to an increment of almost 75 % in the value of the moment resistance. This effect is due to the fact that, when evaluating the resistance of this type of joints, the critical component is the column web panel in shear.

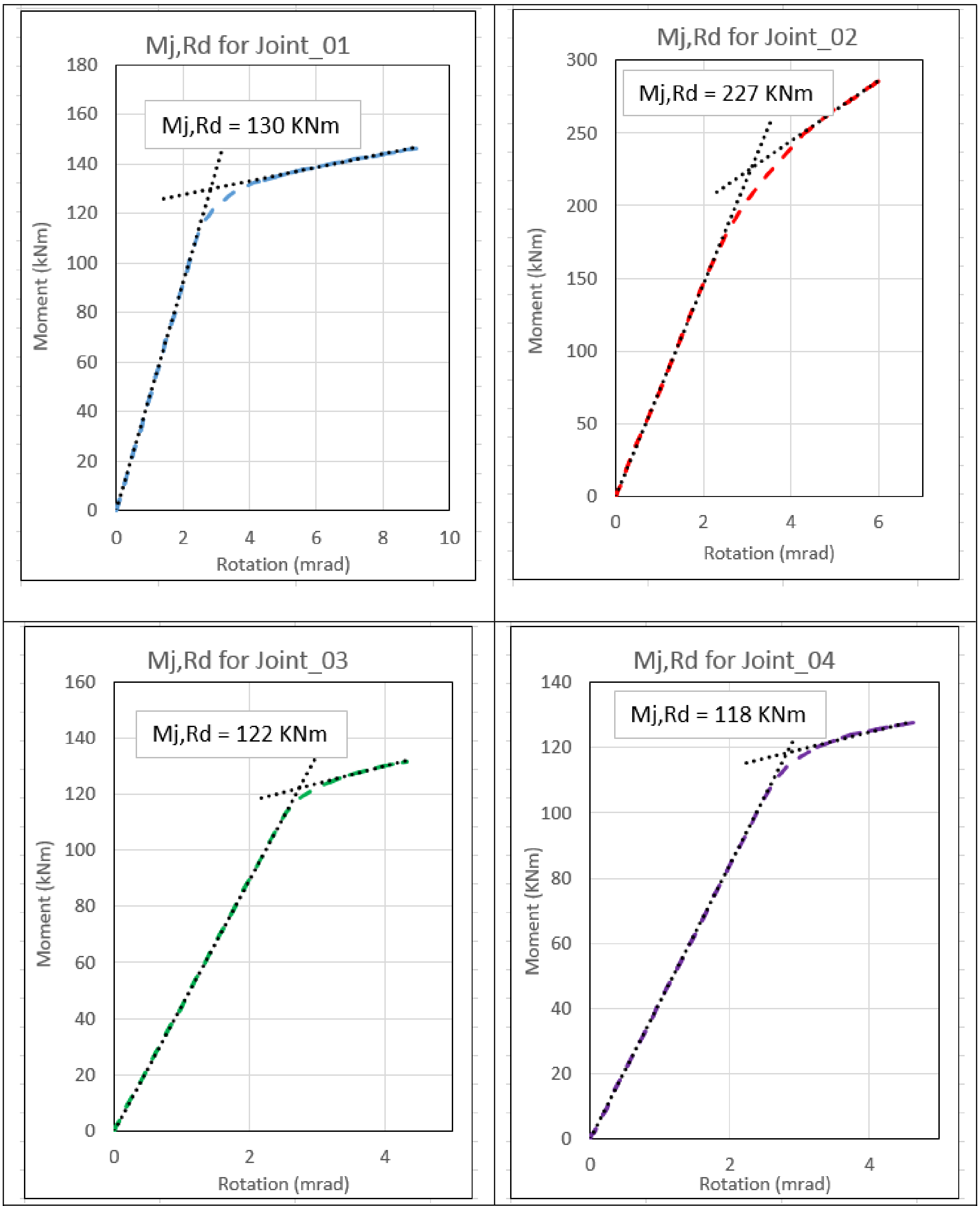


Fig. 9. Calculus of $M_{j,Rd}$ for the different joints

Table 5. $M_{j,Rd}$ values for the studied joints

Model	$M_{j,Rd}$ (KNm)
Model_01	130
Model_02	227
Model_03	122
Model_04	118

4. Condensed matrix and global frame models

As indicated in the introduction of this work, the component method leads to a single rotational spring to simulate the joint behaviour, which is a rather simplistic model of the joint stiffness. Therefore, it is necessary to develop new methods for obtaining the joint stiffness and for introducing such stiffness in the global analysis of the structure. What is proposed in this work for 2D external welded haunched joints, is to model their behaviour by means of the stiffness matrix, condensed to the 9 degrees of freedom that connect the joint with the rest of the structure. Figure 10 (a) shows the 3 nodes of the joint and the corresponding 9 DOF.

The condensed matrix of the joints can be obtained from the finite element models, using the static condensation method, according to the next steps:

First, the matrix equation of the joint is arranged as follow.

$$\begin{bmatrix} Rc \\ Re \end{bmatrix} = \begin{bmatrix} Kcc & Kce \\ Kec & Kee \end{bmatrix} \begin{bmatrix} Dc \\ De \end{bmatrix} \quad (2)$$

Where:
Rc = Load Vector for the degree of freedom (dof) to which we want to condense the matrix.
Re = Load Vector for the dof we want to eliminate.
Dc = Displacement vector for the dof to which we want to condense the matrix.
De = Displacement vector for the dof we want to eliminate.

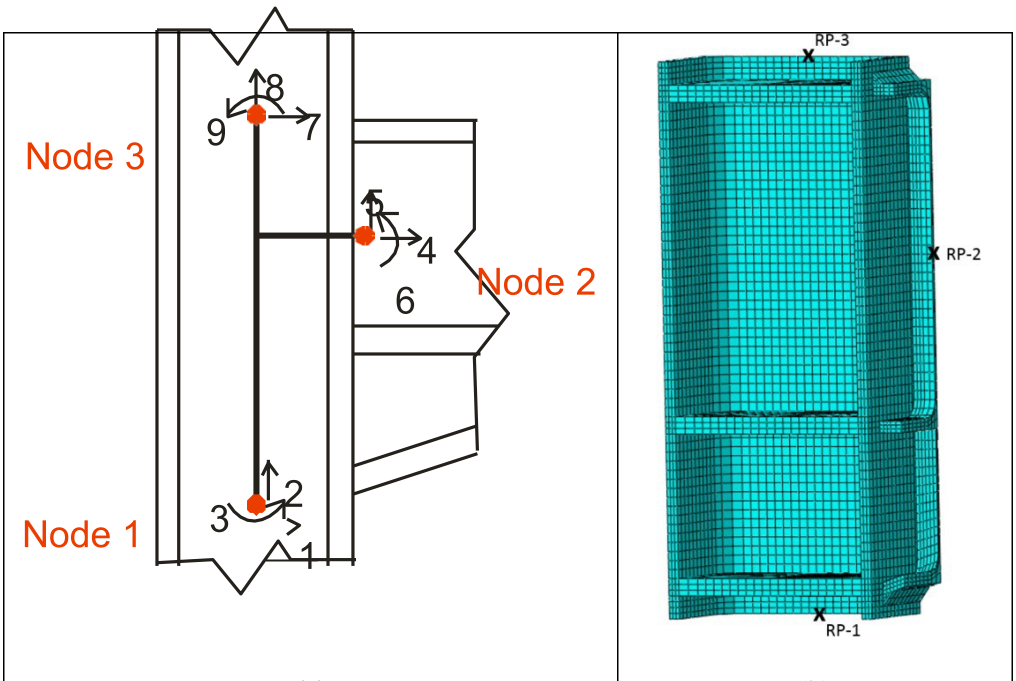
Then, having account that the external forces applied to the DOF we want to eliminate are null, because they are internal dof (Re=0), we have:

$$Re = Kec.Dc + Kee.De = 0 \rightarrow De = - Kee^{-1}.Kec.Dc \quad (3)$$

$$Rc = Kcc.Dc + Kce.De \rightarrow Rc = \left[Kcc - Kce\left(Kee^{-1}.Kec\right)\right].Dc \quad (4)$$

Therefore, the condensed stiffness matrix will be:

$$Kcond = Kcc - Kce\left(Kee^{-1}.Kec\right) \quad (5)$$



(a) (b)

Figure 10. (a) Equivalent 3 nodes and 9 DOF element; (b) Reference points in Abaqus model

In the present work, the static condensation method has been applied by means of the FE software Abaqus®, that offers the possibility of obtaining the condensed matrix ($Kcond$) by means of a "substructure" analysis. This procedure has been widely explained in Bayo and Gracia [25] in their study of 2D symmetrical welded joints, and it has been used by Loureiro et al. [26] for a wide study of asymmetrical welded joints, with very good results.

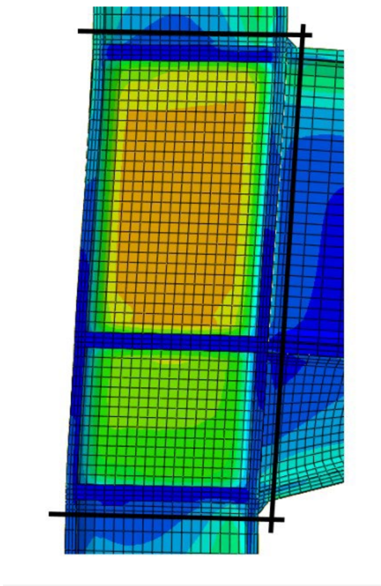
The condensed stiffness matrices of the models (9×9) have been obtained by means of the following steps. Firstly, a linear perturbation step analysis of type "substructure" has been defined. Then the "retained nodal DOF" have been defined in the model. ABAQUS condenses the global stiffness matrix to the selected DOF of the "reference points" located on each rigid surface of the models, as can be shown in Figure 10 (b). Finally, rigid body kinematic constrains have been defined between each reference point and the section (surface) to which it belongs.

ABAQUS calculates the condensed stiffness matrix by means of the keyword '*SUBSTRUCTURE MATRIX OUTPUT, STIFFNESS=YES, OUTPUT FILE=USER DEFINED, FILE NAME=STIFFNESS_MTX'. The "user defined" option, consisting of an ASCII output file format, has been preferred.

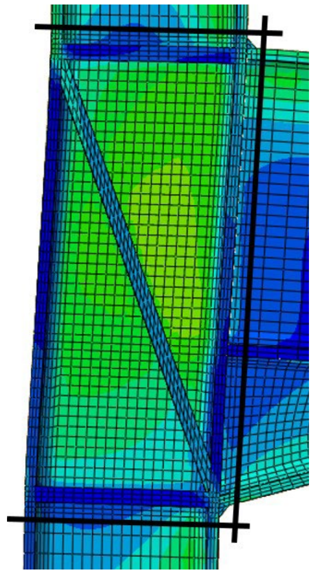
The application of the above mentioned methodology leads to the obtaining of the four condensed stiffness matrices of the joints that can be seen in appendix 1.

In the study of 2D symmetric welded joints without stiffeners, Bayo and Gracia [25] determined that the joint limits should be extended in order to assure the absence of local effects and that plane sections remain plane after deformations. In the present study, all the joints have been extended 10 mm both for the column and the beam, and the compliance of the cited conditions has been verified. To illustrate this point, the deformations corresponding to the end of the elastic regime for the different joints, with a scale factor of 25, are shown in Figure 11. Straight lines have been added to the figures extracted from Abaqus, and it can be seen that the sections remain plane and any local effect has been observed very close to the limits of the joints. Therefore, the cited extension of 10 mm in the dimensions, has been considered adequate for this type of joints.

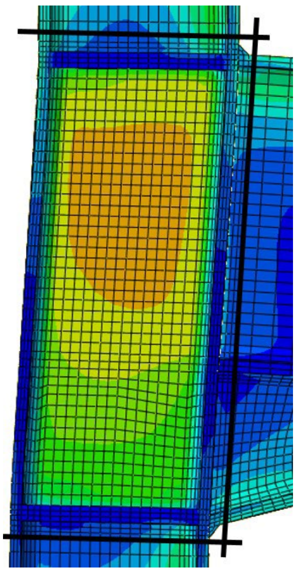
The FE models used for obtaining the condensed matrices are depicted in Figure 10 (b). The FE models included about 12,000 nodes and 17,600 degrees of freedom per model. The average size of the elements is 6 mm. The material behavior has been introduced by means of a linear elastic stress-strain curve. The values adopted for the elastic modulus E and the Poisson ratio ν has been 210,000 N/mm^2 and 0.3, respectively. Rigid surfaces has been attached to the end sections of the joints, and one reference point with 3 DOF has been defined for each of the rigid surfaces, as can be seen in Figure 10 (b). DOF 1,2 and 3 correspond with the reference point 1 located on in the bottom surface of the joint, DOF 4, 5 and 6 correspond with the reference point 2, located on the right rigid surface, and finally, DOF 7, 8 and 9 are located on reference point 3 in the upper surface of the joint.



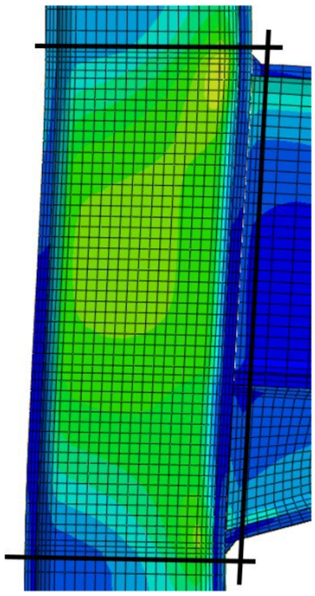
TEST 1 MODEL



TEST 2 MODEL



TEST 3 MODEL



TEST 4 MODEL

Fig. 11 Deformations at the end of the elastic range. Scale factor = 25

It is important to consider that the condensed stiffness matrix models the overall behaviour of the joint into the structure, having account for all the interactions between the 9 degrees of freedom. For checking the performance of the static condensation process, the four tested frames cited in section 2 have been analyzed. Firstly, each frame has been solved with the FE software Abaqus. Then, the condensed stiffness matrix of the joint has been exported to a subroutine of Matlab® software, and it has been assembled with the column and beam, leading to a model with 14 DOF, as it can be seen in Figure 12. Both the FE models and the beam frames have been loading with the same downwards vertical force at the end of the horizontal beam (DOF 11), at a distance of 1 m from the node 2 of the joint. The obtained results are summarized in Tables 6 and

7. Table 6 shows the comparison for rotations of DOF 3, 6 and 9 and the displacement corresponding to DOF 11. In the case of Table 7, the comparison has been done for internal moments in the nodes of the joint, corresponding with moments at DOF 3 and 9.

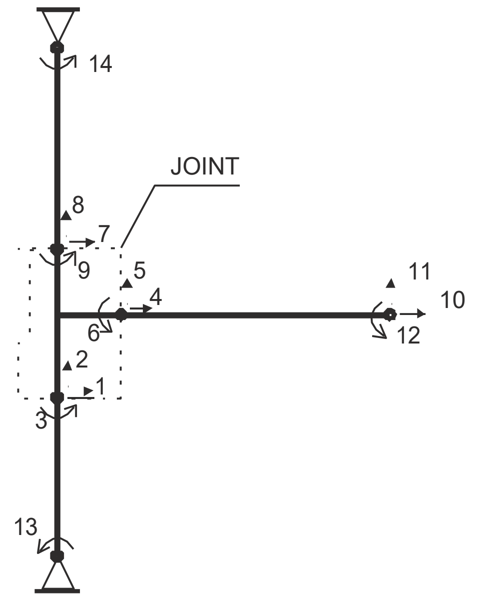


Figure 12. Beam frame of the tests.

It can be seen that the results of Matlab models with the condensed matrix of the joint corresponds very accurately with those of the FE models. The maximum percentage error is minor than 10.1 % in all cases, and the absolute errors are negligible.

As indicated in [2], the classification of the joints as nominally pinned, rigid or semi-rigid, depends on the stiffness characteristics of the connecting beam (Inertia and Length), as well as the level of bracing of the structure. Although in advance it might seem that all the analyzed haunched joints are rigid joints, it has been seen that in the case of bracing frames, the joints 1, 3 and 4 are semi-rigid joints for a beam length smaller than 10 m, while for joint 2, this occurs for a beam length smaller than 6 m. In the case of unbraced frames, these limit lengths are 3.3 m for joints 1, 3 and 4, and 2 m for joint 2. These results show that the actual behavior of the joint may be different depending on the characteristics of the global frame, and it is important to remember that in the case of semi-rigid joints, it is mandatory to introduce the stiffness of the joint in the global analysis of the structure, accordingly with [2]. The inclusion of the actual stiffness of the joint in the global analysis by means of the condensed matrix avoids these problems.

The use of the condensed matrix is valid for all types of joints, including rigid and pinned ones. The replacement of the stiffness of the joint by a rigid or nominally pinned joint is, in some cases, a simplification, and as indicated in [2], rigid or nominally pinned joints may optionally be treated as semi-rigid. The difference between this simplification and the use of real stiffness may not be very significant in some cases, but this doesn't invalidate the use of the proposed method. For clarifying this point, Table 8 shows a comparison between the results of considering a rigid comportment of the joints (infinite stiffness), and the results of considering the real stiffness by means of the condensed stiffness matrix of the joints.

As it can be seen, the errors are very high, and the consideration of rigid joint is not correct in these cases.

Table 6. Comparison of displacements and rotations for FEM and Beam frames

		Φ_6 (mRad)			U_{11} (mm)			Φ_3 (mRad)			Φ_9 (mRad)		
Joint	M_6 (KNm)	FEM	Beam model	Error %	FEM	Beam model	Error %	FEM	Beam model	Error %	FEM	Beam model	Error %
1	80.3	2.50	2.60	4.0	3.91	3.94	0.76	0.97	0.89	-8.1	0.72	0.79	10.1
2	97.1	2.46	2.50	1.6	4.17	4.12	-1.19	1.21	1.11	-6.7	1.13	1.20	7.0
3	78.1	2.53	2.54	0.4	3.91	3.83	-2.04	0.91	0.84	-7.7	0.73	0.78	6.5
4	79.1	2.73	2.58	-5.5	4.17	4.10	-1.67	0.95	0.85	-9.9	0.69	0.75	9.6

Table 7. Comparison of moments in DOF 3 and 9

		M_3 (KNm)			M_9 (KNm)		
Joint	M_6 (KNm)	FEM	Beam model	Error %	FEM	Beam model	Error %
1	80.3	26.35	26.66	1.18	39,52	39,99	1,18
2	97.1	31.87	32.25	1.20	47,80	48,37	1,19
3	78.1	25.63	25.85	0.87	38,44	38,77	0,86
4	79.1	25.96	26.05	0.35	38,94	39,07	0,34

Table 8. Results of rigid joint hypothesis vs real condensed stiffness matrix

Joint	Load (KN)	Φ_3 (mrad)	Φ_6 (mrad)	Φ_9 (mrad)	U_{11} (mm)	Φ_{12} (mrad)
Rigid Joint	80	-1.15	-1.15	-1.15	-2.84	-3.43
Joint 1	80	-0.89	-2.59	-0.79	-4.30	-4.87
Error Rigid vs Joint 1 (%)		28,6	-55,5	45,5	-34,0	-29,5
Joint 2	80	-0.92	-2.05	-0.99	-3.75	-4.33
Error Rigid vs Joint 2 (%)		24,7	-43,8	15,4	-24,3	-20,7
Joint 3	80	-0.86	-2.60	-0.80	-4.30	-4.88
Error Rigid vs Joint 3 (%)		33,7	-55,7	43,6	-34,1	-29,7
Joint 4	80	-0.86	-2.61	-0.76	-4.32	-4.89
Error Rigid vs Joint 4 (%)		33,0	-55,9	50,8	-34,3	-29,9

5. Conclusions

The aims of this study have been:

- To analyze the stiffness and resistance of four different configurations of 2D external welded haunched joints. For this objective, four test have been done and the corresponding FE models have been calibrated.
- To propose the introduction of the stiffness of the joints in the global analysis of the structures by means of their condensed stiffness matrices. For this objective, the condensed stiffness matrices have been obtained using Abaqus software, and these matrices have been introduced in structural analysis simulations with MATLAB, comparing the obtained results.

The main conclusions from this research are:

- The FE results are consistent with tests results and their moment-rotation curves fit very accurately. The analysis of the moment-rotation curves shows that the horizontal stiffeners do not contribute appreciably to the initial stiffness of the joints. However, the diagonal stiffener of the column web produces an increase of 67 % in such stiffness. This fact indicates that the component that govern the stiffness of the joint is the column web panel in shear.
- When analyzing the resistance of the joints, the results present a similar behaviour that those obtained for the stiffness study. The horizontal stiffeners have a very little influence in the resistance of the joint. Nevertheless, the diagonal stiffener leads to an increment of about 75 % in the moment resistance. Again, this effect is due to the fact that the critical component, when evaluating the resistance of the joint, is the column web panel in shear.
- The condensed stiffness matrices include the nine degrees of freedom of the joint, and have into account the interaction between them. These matrices have been introduced in a global structural analysis with MATLAB, and the results have been compared with those obtained by FE models with a very good agreement between the two methods.
- A comparison between the results of considering rigid behavior of the joints and the use of the condensed stiffness matrix has been performed. The results show that the consideration of rigid joint behavior leads to important errors.
- The use of the condensed stiffness matrix is valid for pinned, semi-rigid and rigid joints, avoiding the necessity of classifying the joint.
- The proposed method could be easily applied to any type of joint, including 3D joints, and implemented in structural analysis programs, avoiding the application of the component method.

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Appendix 1. Stiffness matrices of the joints.

In this appendix the condensed matrices extracted form Abaqus software are presented. These matrices must be multiplied by 2, because symmetry respect to the middle plane of the joints has been used. The units for the different components are N, Nm and m. The DOF correspond with those indicated in Figure 10(a).

Stiffness matrix for joint 1

1907754,63	638739,626	80168,174	-1534531,48	-721986,838	-567884333	-373223,148	83247,2126	-5578209
638739,626	2226464,53	119870444	-538290,131	-1932011,48	-137596870	-100449,495	-294453,051	26014869,9
80168,174	119870444	2,6703E+10	-2276351,07	-146608952	-4957086572	2196182,89	26738507,6	-4388289361
-1534531,48	-538290,131	-2276351,07	3274784,61	56086,852	178462691	-1740253,13	482203,279	-3036410,88
-721986,838	-1932011,48	-146608952	56086,852	3847750,25	184660015	665899,986	-1915738,77	-145983288
-567884333	-137596870	-4957086572	178462691	184660015	2,2895E+11	389421642	-47063145,5	-2211723660
-373223,148	-100449,495	2196182,89	-1740253,13	665899,986	389421642	2113476,28	-565450,491	8614619,88
83247,2126	-294453,051	26738507,6	482203,279	-1915738,77	-47063145,5	-565450,491	2210191,82	119968418
-5578209	26014869,9	-4388289361	-3036410,88	-145983288	-2211723660	8614619,88	119968418	2,6742E+10

Stiffness matrix for joint 2

2045302,14	794250,441	3779635,14	-1556402,14	-983511,151	-607650687	-488900	189260,71	-708440,978
794250,441	3728230,41	215814245	-647244,4	-2777252,75	-221712056	-147006,041	-950977,659	56927145,5
3779635,14	215814245	3,4896E+10	3453126,12	-218605874	-1,1119E+10	-7232761,26	2791629,1	-778361708
-1556402,14	-647244,4	3453126,12	3202420,67	-9598,48072	205382111	-1646018,53	656842,88	-6748728,51
-983511,151	-2777252,75	-218605874	-9598,48072	5502441,94	245188144	993109,631	-2725189,19	-190542632
-607650687	-221712056	-1,1119E+10	205382111	245188144	2,4983E+11	402268576	-23476087,7	-9554373761
-488900	-147006,041	-7232761,26	-1646018,53	993109,631	402268576	2134918,53	-846103,59	7457169,48
189260,71	-950977,659	2791629,1	656842,88	-2725189,19	-23476087,7	-846103,59	3676166,85	133615486
-708440,978	56927145,5	-778361708	-6748728,51	-190542632	-9554373761	7457169,48	133615486	3,3982E+10

Stiffness matrix for joint 3

2021788,31	911917,06	11904248	-2023089,37	-924171,701	-542368128	1301,05911	12254,6412	-2005070,7
911917,06	3265896,13	162470884	-906348,805	-2556902,67	-183470329	-5568,25444	-708993,469	28023449,3
11904248	162470884	2,8397E+10	-13977595,4	-190320847	-6621017638	2073347,34	27849962,8	-3110898707
-2023089,37	-906348,805	-13977595,4	4758965,68	-28970,2639	172815259	-2735876,32	935319,069	15627883
-924171,701	-2556902,67	-190320847	-28970,2639	5290439,26	244443028	953141,965	-2733536,6	-211848945
-542368128	-183470329	-6621017638	172815259	244443028	2,1807E+11	369552868	-60972698,3	-4762770721
1301,05911	-5568,25444	2073347,34	-2735876,32	953141,965	369552868	2734575,26	-947573,71	-13622812,3
12254,6412	-708993,469	27849962,8	935319,069	-2733536,6	-60972698,3	-947573,71	3442530,07	183825495
-2005070,7	28023449,3	-3110898707	15627883	-211848945	-4762770721	-13622812,3	183825495	3,0746E+10

Stiffness matrix for joint 4

1378081,29	605313,425	7297479,43	-1074471,05	-743049,587	-425834707	-303610,243	137736,161	2904043,64
605313,425	2144418,46	114150278	-439415,717	-1896778,06	-148303152	-165897,709	-247640,404	28567033,2
7297479,43	114150278	2,5286E+10	-479877,426	-143536988	-8244945030	-6817602,01	29386710,1	-3906983529
-1074471,05	-439415,717	-479877,426	2308046,03	2413,08822	139649540	-1233574,99	437002,628	-193496,84
-743049,587	-1896778,06	-143536988	2413,08822	3787158,23	215169137	740636,499	-1890380,17	-142264443
-425834707	-148303152	-8244945030	139649540	215169137	1,776E+11	286185167	-66865984,8	-6249148494
-303610,243	-165897,709	-6817602,01	-1233574,99	740636,499	286185167	1537185,23	-574738,79	-2710546,8
137736,161	-247640,404	29386710,1	437002,628	-1890380,17	-66865984,8	-574738,79	2138020,57	113697410
2904043,64	28567033,2	-3906983529	-193496,84	-142264443	-6249148494	-2710546,8	113697410	2,5281E+10

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